THE APPLICATION OF SOCIAL COST BENEFIT ANALYSIS

TO

NUCLEAR POWER IN THE UNITED KINGDOM

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Abstract

The Application of Social Cost Benefit Analysis to Nuclear Power.

This thesis presents an economic analysis of interfuel substitutability and of capital/labour/fuel substitutability in the production of electricity in England and Wales, 1963/64 to 1982/83, and establishes a methodology for the economic assessment of the growth and future development of the civil nuclear power industry. While the approach is applied to the case of the UK, it may be used for any country and for comparative studies. The analysis falls into two separate (but interrelated) sections. The first of these is the econometric analysis. The choice of theoretical model finally estimated arises from investigation of the relative merits of various production functions. It is concluded that the transcendental logarithmic function has the most desirable properties, both methodologically (in that it involves the least initial constraints on the data, and allows sequential testing of nested hypotheses), and analytically, as it permits the estimation of parameters directly relevant to the theme of the thesis. These are the own- and cross-price elasticities of demand for the inputs, and the partial elasticities of substitution between inputs. Existing literature on energy/labour, energy/capital substitutability is reviewed. The results of the estimation reported here provide new information on interfuel substitution possibilities and on the substituability or complementarity between the major inputs to the production process.

The second section applies economic theory to characteristics of particular relevance to the case of nuclear power, and extends the analysis to provide the methodological framework for appraisal of nuclear power projects. Intertemporal problems are assessed by using the concept of option value (which has been used to a limited extent in natural resource economics, but not in the case of nuclear power), and in demonstrating how public sector investment appraisal techniques must be adjusted. The roles and significance of forecasting, externalities and planning inquiries are analysed to complete the policy implications of the methodology developed in the thesis.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF ABBREVIATIONS

ACS	Average Cold Spell
AGR	Advanced Gas Cooled Reactor
BNFL	British Nuclear Fuels ltd.
BNOC	British National Oil Corporation
BTU	British Thermal Unit
BWR	Boiling Water Reactor
CANDU	Canadian Deuterium-Uranium Reactor
CD	Cobb Douglas
CEA	Commissariat à l'Energie Atomique Central Electricity Authority
CEGB	Central Electricity Generating Board
CES	Constant Elasticity of Substitution
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COGEMA	Compagnie Générale des Matières Nucléaires
DPC	Discounted Payback Criterion
EC	Electricity Council
EDF	Electricité de France
ESI	Electricity Supply Industry
FBR	Fast Breeder Reactor
GDP	Gross Domestic Product
GNP	Gross National Product
GW	Gigawatt
GWh	Gigawatt hours
HARVEST	Highly Active Residues Vitrification Engineering Studies
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IRR	Internal Rate of Return
KWh	Kilowatt hour
LWR	Light Water Reactor
MMC	Monopolies and Mergers Commission
MTC	Million tonnes coal
MTCE	Million tonnes coal equivalent
MW	Megawatt
MWe	Megawatts electric
MWh	Megawatt hour
NAC	Net Avoidable Cost
NCB	National Coal Board
NEA	Nuclear Energy Agency
NEC	Net Effective Cost
NEDC	National Economic Development Council
NII	Nuclear Installations Inspectorate
NO_x	Oxides of Nitrogen
NPV	Net Present Value

NUM	National Union of Miners
OPEC	Organisation of Petroleum Exporting Countries
PDR	Political Discount Rate
PPC	Project Payback Criterion
PWR	Pressurised Water Reactor
RRR	Required (Real) Rate of Return
SCBA	Social Cost Benefit Analysis
SDR	Social Discount Rate
SO_2	Sulphur Dioxide
SOC	Social Opportunity Cost
STPR	Social Time Preference Rate
THORP	Thermal Oxide Reprocessing Plant
TWh	Terawatt hour
UKAEA	United Kingdom Atomic Energy Authority

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CHAPTER I

INTRODUCTION

I.1 OVERVIEW

The Electricity Supply Industry of England and Wales publishes annually, through the Corporate Planning Unit of the Electricity Council a Medium Term Development Plan, covering its future plans over a seven year period. The 1985-92 document (1) notes that "coal and uranium will continue to be the principal fuels for electricity generation" (2), and proposes as one of its "key actions" that of "maximising electricity production from nuclear power stations presently under construction and those in service, consistent with safety and economy" (3). Its other, major nuclear plan depends on the outcome of the Sizewell B Public Inquiry; should that be favourable, the Plan envisages maximising "economic benefit from the introduction of PWR technology by proceeding as rapidly as possible with a "minimum family of 4 or 5 PWRs to replicated design" (4). It is clear that the role of nuclear power in the overall supply of electricity will be promoted and expanded; this thesis assesses the economics of that role to date, and discusses the means by which the economist may undertake analysis of the proposals from the Electricity Supply Industry.

Since 1963/4 when nuclear power stations supplied 3,102 GWh in England and Wales (representing 2.2% of total supply), their relative importance has grown fairly consistently, so that by 1983/4 they supplied 31,260 GWh (or 13.6% of the total) (5). Over the same period, the share of electricity in total secondary energy consumption in the UK has risen from 9% to over 14% (6). The significance of both total energy and electricity to overall economic activity is highlighted by the OECD Steering Committee for Nuclear Energy: "Sustained economic growth is critically dependent on the availability of adequate energy supplies. In particular continued progress in assuring energy supplies for the OECD area requires further and prompt expansion of nuclear and coal capacities" (7). There is now a coherent argument: a major objective for the UK is continued economic growth. A necessary condition for such growth to take place is an adequate total energy supply; and a requirement for this is expansion of the nuclear fraction of electricity supply, and of overall electricity availability. Here is a powerful justification of the proposals from the ESI referred to above. It is not, however, accepted without question by all. It is a contention of this thesis that a Social Cost Benefit Analysis (SCBA) of nuclear power would be required to examine the above argument in the light of the alternative criticisms, which have been developed particularly since the first OPEC oil price shock of 1973/4.

The main issues would be firstly the role of energy and economic growth. Energy use and GDP grew together so closely in post-war UK history that it became easy to explain the link between them as causal, just as the OECD (1982) paper quoted above does. The linkage was severely damaged if not irrevocably broken in 1973/4 and the point at issue is whether or not the GDP growth/energy supply growth relationship should be considered inevitable. Second, the role of electricity within total primary energy supply is another point of contention. As noted above, market penetration of electricity has grown over the last two decades. Such growth is justified in a number of ways: to a large extent supply may be said to be demand determined. Not only does the ESI have a statutory duty to meet all demands for electricity made on it, (the timing of which demands it can, of course, attempt to shift by its pricing policies), but it may also be argued that peoples' choice should not be questioned. That is, provided relative energy efficiencies are made public knowledge, and grossly inefficient usages are deterred (by taxation, for example), individuals may be assumed to be maximising utility in their choice of energy consuming goods, and such choices are not for the State (and certainly not the ESI) to question. In addition electricity's popularity derives from its properties as a clean, versatile and highly efficient end-use form of energy. The debate here concerns, essentially, how satisfactory or desirable it is to meet energy needs by electricity, given that even the best of our power stations operate at about 35% efficiency. Underlying the criticism of points one and two is a view that continued growth of the economy, of the technology that that growth develops, and of the centralisation of policy and decision-making that that technology encourages are all undesirable.

Finally there arises the issue of the role of nuclear power in the overall production of electricity. Its expansion is predicated on its cheapness and on the safety of the technology; furthermore that technology relies on an abundance of fuel and may be developed to a stage, (the breeder reactor), which extends the availability of fuel quite enormously. The counter arguments in this case concern the questions of whether nuclear stations' overall costs may be so great as to outweigh the relative fuel-cheapness; the safety of the entire nuclear fuel cycle; the significance of radioactive waste and the many intangible costs (and benefits) relating to electricity production in general and nuclear power in particular.

Econometric analysis can be used to investigate some of the above claims. In this thesis it is used specifically to analyse the operating conditions of the ESI since 1963/4 and to do so by the estimation of own- and cross-price elasticities of demand for the inputs and of the partial elasticities of substitution between them. This approach is particularly important as the estimates derived produce evidence on whether any given pair of inputs are substitutes or complements and on the degree of the relationship. There has been a growing debate recently in the energy economics literature concerning the substitutability/complementarity of energy and other inputs at both the economy-wide macro-level and in disaggregated studies (8). The contribution that the econometric analysis presented here makes, lies in its analysis of the possibilities for interfuel substitution in electricity production in the UK and of the relative substitutability of 'fuel' (an aggregate index derived from coal, oil and nuclear fuel) with the broad factor classes of labour and capital. Such an analysis has not, so far, been presented, and is of direct relevance to the consideration of a SCBA of the development of nuclear power in the UK, and, hence, it is of significance in the formulation of energy policy.

The econometric results and estimating equations might also be used for forecasting purposes. Forecasting itself is of fundamental importance to the ESI whose principal investment projects - power stations - have long lead times (five to ten or more years) and an operating life expected to be at least 25 and probably 30 years (9). At the very least forecasts need to be able to give satisfactory guidance ten years ahead, and arguably a system simulation over twentyfive to thirty years should be a cornerstone of the investment decision. When past forecasts are judged against the actual outturn, it becomes clear that capacity for error in this area is substantial and that learning from successive error is a slow process. This is not unique to the UK ESI but is an obvious and generic problem of attempting any forecast beyond the short term; a problem worsened in this case by the energy price shocks, recession and enforced (and chosen) conservation of the 1970s and early 1980s. The overwhelming problem is of uncertainty, and clearly, any econometric forecasts produced must be subjected to sensitivity analysis to examine how robust they are to changes in the assumptions on which they are based. An alternative (or perhaps complementary) approach is to formulate 'scenarios' whose frameworks are based on alternative sets of assumptions concerning the movements in the major exogenous variables. "High" and "Low" case scenarios will set the bounds between which the actual outcome is expected to fall and the policy-makers may decide on the plausibility of the interrelated movements of the independent variables and so determine the most likely scenario.

A second area where uncertainty becomes of major importance lies in investment appraisal procedure - in particular in the choice of discount rate. The general, theoretical debate concerns the question of whether in the face of risk and/or uncertainty, an accommodating alteration should be made to the discount rate. Since forecasting has been seen to be an especially difficult problem for the ESI, with uncertainty assuming a dominant position, associated theoretical conclusions concerning the formulation of the investment appraisal under uncertainty are of major importance. Taken alone, sensitivity analysis, or limiting the time horizon by an arbitrary cut off point are inadequate means of dealing with uncertainty, and the investment appraisal method must also be considered as part of the adjustment made necessary by uncertainty.

Although the necessity for an economic analysis of nuclear power to be made via a SCBA has been stressed, with the exception of the intangible effects of electricity production, the discussion so far could relate to a straightforward piece of accounting rather than to economic evaluation. However, nuclear power does have some special features which mean that the only satisfactory analysis of the desirable rate of construction and operation of nuclear plants must be economic. This means that intangible costs and benefits must be explicity defined, even if valuation proves difficult or impossible (10); and, as an extension of this, the different attitudes to the desirability or otherwise of economic growth, of the development of 'hard' technology, of the growing complexity, specialisation and hence impenetrability (to the layman) of modern technology must also be openly considered. The concept of 'externality' may be applied very broadly and, unless account is taken of such effects, an area of major significance will simply be ignored. As Seneca and Taussig (1984) argue: "The benefit-cost framework is indispensable to the proper conception of [environmental] problems and enables economists to ask the right questions even if they are not yet able to provide the correct answers" (11).

The earlier discussion of uncertainty is, of course, not confined to nuclear power, but will be common to large-scale technology where capital intensity tends to imply both a long lead-time and a long economic life. Forecasting within a scenario framework and adjusting the discount rate to accommodate risk can be applied generally. There are two additional elements here which single out nuclear power for economic analysis. The first is the problem of intergenerational equity which is raised in this context because of the possible irreversible impacts that the introduction of civil nuclear power has.

These relate to the creation of waste which must be stored for very long periods and eventually sealed in a depository, which will need to be safeguarded in some way from then onward. The question at issue is not whether technological developments are such that a permanent solution is now virtually developed, but whether it is inequitable to impose on future generations the inevitability of dealing with waste created now. Nuclear waste is an 'irreversible effect' in that the half-life of many of its constituents is such that once created, the waste - however safe current disposal methods may be considered to be - becomes a permanent feature. In this way a decision to go forward with nuclear power development now presents future generations with lost options - that of not dealing with radioactive waste, and the possibility that future technology may prove incapable of dealing with the waste and the need to decommission stations at the end of their useful life. However failure to undertake the development now may also involve costs - perhaps those of a slower growth rate because of inadequate energy supplies, so that current and immediately succeeding generations are poorer than would otherwise have been the case. Morowski (1983), for example, argues that despite adequate current capacity in the USA even moderate growth of demand will lead to inadequate supply fairly soon, implying that the 'planning window' for development is quite narrow and limited; the implication being that if the window is missed, the delay will impose costs on all (12). Additionally, it is sometimes argued that unless new nuclear undertakings are permitted to go ahead (such as the PWR at Sizewell) they may be delayed, perhaps for good. If so, alternative and sub-optimal methods will be used to provide power less efficiently and at increased cost.

The economic interpretation of these considerations lies in the analysis of option value and one section of this thesis extends that analysis to the case of nuclear power, showing how it may be applied and its significance for a SCBA.

A point closely related to the general consideration of risk and uncertainty is the problem of safety within the nuclear industry and public attitude to risk. Safety may seem to be an essentially technical matter and Greenhalgh (1984) criticises the approach of the Sizewell B Inquiry for attempting to examine points of contention between the CEGB and NII which may be "of considerable technical complexity" and are "almost all matters of opinion and judgement rather than of scientific fact" (13). There is, instead, an important economic element to safety; as Greenhalgh (1984) notes, a superior approach for the Inquiry to have taken would have been to examine the investigative methodology used by the NII and whether or not the NII had the resources to undertake its safety analysis.

The second economic impact of safety analysis lies in the extra expenditure entailed in incorporating increasingly strict conditions. In the case of the LWRs built in the USA, Freeman (1983) argues that the original designs were not sufficiently safety-conscious and the resultant retrofitting has proved both extremely expensive and effectively open-ended. The result has been that utilities who were prospective buyers of new nuclear plant have decided it would now probably prove uneconomic. Komanoff (1980/81) argues strongly that nuclear plant capital costs rose in the 1970s more than twice as fast as those of coal plants, primarily because of changes required to meet ever-developing safety requirements.

Since it is always possible to spend more on safety, the question of when the current safety levels are satisfactory arises. Radiation release levels might then be determined by an 'as low as reasonably achievable' criterion and this leads to the final economic element in safety analysis which is the way individuals evaluate risk. Risk analyses carried out by the industry consistently show high loss accidents to have tiny probabilities and hence tiny expected values. Equally consistently private individuals over estimate those probabilities and attach far higher expected values to the consequent costs. Clearly, risk perception is entirely different between the two groups and results in immensely divergent economic analyses of any given project. Once again, a disinterested SCBA can give due weight both to the objectivity of the industry risk analysis (14) and to the subjective, but, nevertheless, highly important attitudes of private individuals to perceived risk.

A final problem area which would fall within the ambit of a SCBA is that of terrorism and weapons proliferation. These are both discussed at some length in Flowers (1976) and some authors (15) go so far as to argue that the problems of increased risk of war and decreased civil liberty which surround the nuclear debate render SCBA impossible. In contrast, Maxey (1979) argues that plutonium is not unique as a substance which can be used to make weapons; mankind has a very great ability in such manufacture and the true test is not to ban the by-product of a vital source of energy, but to devise international political and social institutions and safeguards to "govern all ... potential sources of weaponry" (14). It may also be questioned whether the weapons argument is symmetric. Increasing civil nuclear power programmes is said to increase the risk of proliferation of weapons by making their raw material more available. But is it the case that inhibiting such programmes would reduce the production of weapons, or the likelihood of conflict using them. It may equally well be argued that the nuclear weapons 'industry' has a momentum all of its own, and may be seen by those within and controlling that 'industry' as entirely distinct from civil and economic considerations. Just as has been the case above, contrasting arguments may be presented for evaluation, and that is the task which the SCBA is ideally suited to achieve. Making intangibles explicit is a major part of the function a SCBA has to perform, and of its value.

In the absence of a full SCBA the two most recent nuclear industry investment decisions - the Thermal Oxide Reprocessing Plant at Windscale and the PWR at Sizewell - have been the subject of substantial Planning Inquiries (17). The then Secretary of State for Energy Mr D. Howell announced the Sizewell B Inquiry in December 1979, stating that he wanted it to be "full thorough and fair". As a result "the breadth of the subject matter open to examination was wide and the choice of what to examine was not limited" (18). The Inquiry was intended (and attempted) to cover "the CEGB's need for the station to provide secure and economic electricity supplies, safety features ... waste management ... (and) local issues" (19). The Inquiry opened on 11 January 1983 for the start of the main hearings, and closed on 7 March 1985 after 340 working days. The Planning Inquiry system was designed to deal with local issues but has in this case been dramatically broadened. So much so that many commentators (20) argue that one result of this case will be that more of the debate will be returned to Parliament and the Planning Inquiry will revert to its local issues role. It clearly faces a substantial problem as now organised. Who decides where the border between national needs and local issues is placed? How can a legalistic approach cope with political argument? Alternatively, has the effect of the Inquiry been to politicise factual argument? Chapter VI discusses the issue and argues that a Planning Inquiry may attempt some of a true SCBA but cannot perform it properly; hence it falls between two stools and inevitably attracts criticism for its equally inevitable failure.

I.2 FRAMEWORK

I.2.1 Econometric Analysis

The economic theory of production points to the analytical importance of a series of elasticity measures, and in particular to the information on the relative ease of input substitutability provided by the partial elasticity of substitution. Empirical investigation of the value of this elasticity, together with values of price elasticities has an important policy significance in indicating, in the case of electricity, the scope for substitution between fuels, and between energy, capital and labour.

Recent theoretical developments have led to the transcendental logarithmic (translog) model, which offers a set of benefits to empirical analysis. First it permits a two stage estimation process, analysing initially the fuel inputs (coal, oil and nuclear fuel) and then the overall function (labour, capital and fuel). Thus, all the elasticity estimates are available for both the fuel subsystem and the complete production process. Second this is a flexible model and does not begin with the constraints on empirical work imposed by such functional forms as the Cobb-Douglas or constant elasticity of substitution functions. The model may be estimated in its most general form and restrictions imposed and tested; nested hypotheses may be tested sequentially, hence the model demonstrates a satisfactory econometric methodology.

Third, there is a growing body of literature using this model in the field of energy economics (reviewed in Chapter II), but it has not been applied to nuclear power. Finally, duality theory may be used to move from consideration of the production function to the cost function. This is desirable as factor prices may reasonably be assumed to be exogenous whereas input quantities may not. The translog model is not self dual, so estimates derived from the cost function analysis will not, in general, be the same as those derived from the production function analysis. This is not a disadvantage as the exogeneity of factor prices determines the choice of cost function for empirical work.

A possible disadvantage of the translog model is that it assumes profit maximising, competitive behaviour on the part of the industry it is being used to investigate. The CEGB is a monopolist in selling electricity; an overwhelmingly important buyer of coal, and a monopsonist in the UK for uranium, (bought through the British Civil Uranium Procurement Directorate acting on the Board's behalf). However, electricity has to be competitive with other energy sources (and its relative success is discussed in Chapter VI), and there is some argument that in the future NCB prices will be forced to reflect world coal trade prices. Prior to 1973/4 oil was a low price fuel whose real price had been falling; the opportunity for coal prices to rise in the wake of oil prices has not had a long history, particularly as oil price began to fall in real terms in 1985, and have been falling very markedly in 1986.

The process of estimation of the model and the results are presented in Chapter III. There were particular difficulties associated with the estimation; the first of these was strong evidence of multicollinearity in both sets of independent variables, with the problem appearing to be worse in the fuel subsystem equations. In addition nuclear power has not contributed to total output for long so the sample size was limited and throughout the relative share of nuclear fuel in total expenditure is small and swamped by the coal share. In both systems of equations the restriction of symmetry is rejected contrary to the economic theory. Following Hamermesh and Grant (1979) it was decided to let theory and knowledge of the data dictate the model; the sample size and possible unreliability of some of the data (the nuclear fuel price data are derived via several transformations of the published data), mean that a 'fairly close' rejection of the symmetry restriction may be ignored.

There was also the problem of the obvious structural break in 1973/4. This could have been made the subject of a straightforward Chow test, but splitting the sample would leave two subsamples of 11 and 9. Given the number of regressors, the degrees of freedom would have been so low that while such a test would be possible, it is very doubtful that it could usefully have been said to have achieved anything.

The results are listed and discussed in Chapter III. The most interesting and significant results come from the overall equations where the post 1973/4 estimates on factor substitutability and complementarity change dramatically.

I.2.2 Intertemporal Problems

Intertemporal allocation and the nuclear power investment decision is a wide ranging problem covering investment appraisal techniques; special problems for public sector appraisals; the overwhelming influence of risk and uncertainty; and the intergenerational equity considerations raised by the irreversible nature of the consequences of going ahead with nuclear investment.

The question of the role of the discount rate in SCBA is concerned specifically with the length of time involved - a thirty year period for operation of the power stations and waste storage/disposal operations into the distant future. The debate has two elements: one is whether the standard investment appraisal is satisfactory or whether a zero (or even negative) interest rate should be used to counter the effect of a large discount factor for long periods ahead rendering trivial any costs to be faced then. It might be argued that this problem is best dealt with by the market (a point taken up in a different context in Chapter VI). Thus, the capital market will produce an interest rate which measures society's marginal rate of time preference (and of time productivity) - if it failed to do so there would be adjustment caused by the resultant flow of lending and borrowing. However, not only is the market imperfect, shifting continually and offering many possible rates, people's views of the future are also imperfect, meaning the market rate will be subject to some adjustment within a SCBA.

The second element is the question of how risk should be accommodated - should the interest rate used in public sector investment appraisal be an explicity risk-adjusted rate; or should the approach be to assume that government projects are essentially risk free as their costs and benefits are spread over the entire population? Consideration of the role of risk leads to a related area of difficulty: the problem of the options for present and future generations that are either removed or made available by nuclear power. Failure to develop now could mean no future development (as design and construction ability is lost) or, at least, much delayed development. The loss suffered in terms of foregone economic growth measures the option lost in consequence. Alternatively, the decisions to go ahead may be found later to have been in error and the extra costs (irreversible change to the environment, and lack of development of alternative energy sources) again measure the lost option. Application of the concept of option value highlights the economic meaning of many arguments on the speed at which nuclear power should be expanded, and clarifies the need for, (and direction of) adjustment of cost estimates made within a SCBA.

The fundamental importance of risk and uncertainty in intertemporal analysis is stressed throughout Chapter IV, and in an appendix the economic issues surrounding the major risk areas apparent in nuclear power are discussed.

I.2.3 The Economics of the Nuclear Fuel Cycle

Chapter V has four major objectives which all revolve around its presentation of the cycle which runs from mining uranium ore, through the production of electricity from the heat geneated by nuclear fission in a reactor to dealing with the spent fuel. The first objective is to put the remainder of the thesis into context by outlining the various processes involved in the front and back ends of the nuclear fuel cycle. This also covers fuel preparation for different types of reactor: currently in the UK there are two commercial types, Magnox which use natural uranium and the Advanced Gas Cooled reactors which use (slightly) enriched uranium. Both types are gas-graphite, but if the Sizewell B Inquiry conclusion is favourable to the CEGB, a third type - the Pressurised Water Reactor - (also using enriched uranium) will be introduced. The alternatives of storage and disposal of spent fuel, or reprocessing, (storage and disposal) are also considered.

The second objective is to demonstrate the range of cost estimates that have been made for different stages of the fuel cycle. As is generally the case in the analysis of natural resources, these estimates are peculiarly economic, being based to a large degree on prior assumptions about the pace of development both of the economy as a whole and of the electricity industry and on the speed of market penetration of electricity. The quality of economic forecasting and the assumptions on changes in exogenous variables determine these estimates.

The costs derived for each stage are subject to inflation, to changes in international relations and trade and to varying degrees of commercial (and governmental) secrecy. Therefore, it is not the task of this chapter to provide a comprehensive and current statement of all cost estimates. Not only would such a statement rapidly become unreliable but the UK industry is in the process of substantial change. There has been immense and unexpected delay over the Sizewell B Inquiry, and there is a reorientation of the fast breeder research programme toward a joint European approach. The cost estimates given are meant as general guidelines to show the varying scale of expenditure at different stages of the cycle.

The fourth objective is to present a preliminary indication (and in some cases assessment) of the problems specific to the growth of civil nuclear power in the UK. These include management of waste; of radiation releases from power stations; of terrorism and proliferation; of reprocessing and the 'plutonium economy'. Some of these considerations verge on moral issues, all converge to present a powerful case in favour of conducting a full social cost benefit analysis.

Thus, this chapter is partly descriptive and partly analytical. Its theme is the nuclear fuel cycle and its conclusion lies in the evidence it presents in favour of economic analysis of the growth of civil nuclear power.

I.2.4 Policy Implications

The theme of this thesis is that civil nuclear power has characteristics which make a SCBA a fundamentally importance influence on policy making. The final chapter seeks to delineate the remaining relevant areas and to justify the use of the cost-benefit approach. The first of these areas is that of energy supply. Here it is argued that a SCBA would need to consider the overall supply/demand position for energy, then the likely future penetration of electricity into that energy market and finally the share of nuclear power within the electricity sector (21). Schurr (1984) argues that policies formed now will determine supply in times when North Sea output is in decline and when environmental concerns have grown, so the objective of such policies must be to meet supply constraints and environmental constraints acceptably. Ramsey (1979) also argues that a decision of some sort must be taken, and his solution to the problem of uncertainty and the current weakness of scientific and economic knowledge in the area of health and environmental damage control is to provide for more rather than less pollution abatement measures. However, if this approach is followed for determining supply, it will lead to the development of excess capacity. The Select Committee on Energy (House of Commons (1981)), argued that the current planning margin of 28% represented "a dramatic waste of investment" (22) and that the ESI should be more concerned with system reliability which would lead to a lower planning margin being required. As Ince (1982) also points out, the large unit size of generating sets is itself a reason for an increased planning margin as the failure of a large unit means a big percentage loss of output.

The Select Committee also pointed to the then CEGB nuclear investment plans representing "a pre-emption of a large slice of the nation's resources which might otherwise be available for investment in other parts of the economy" (23). This is as clear a statement as possible of the central role of economic analysis in energy planning. Moreover, Pearce and Jones (1980) demonstrate how inconsistencies between supply forecasts and government statements of intent in nuclear development can be shown up by an economist's investigation of the practical investment implications of such proposals.

Forecasting in general is an area where the CEGB and ESI have performed poorly and appear to have learnt slowly from past errors. Franklin (1985) argues that the forecasting "metholodogy tends to encourage the forecaster to study in detail those factors that are capable of quantification, and to ignore the rest ... especially when the rest relate to subjective matters such as learning curves, industrial motivation ... " (24); and Bajay (1980) notes that "the demand estimation exercise has only lately become something other than extrapolations of past trends sometimes tempered by oversimplified correlations with indicators of economic performance" (25).

However, these forecasts have to be made over extraordinarily long periods and their failure is highly likely. The alternative approach of forming forecasts within scenarios allows investigation of a broad band of possible future events, but still leaves the problem of which scenario to choose as the most plausible to act as a basis for investment decisions. That difficulty notwithstanding, Franklin's view is another clear statement of precisely how important an economic analysis of costs and benefits is.

Environmental concerns are also prominent in nuclear power development programmes. Local communities (particularly) feel disadvantaged if a power station is proposed for their area, expecting lower property values, loss of scenic beauty, fear of pollution, but little extra employment or income. These local fears may cause (lengthy) delays in planning consent and hence reduce electricity's opportunity for market penetration. Problems such as these are the precise area of analysis for a SCBA; as Mishan (1982a) argues: "the least [the economist] can do is to reveal clearly the area of ignorance" (26). Komanoff (1981) notes that there is no answer to the question of whether nuclear power plants are safe or unsafe, but it is clearly within the scope of economic investigation to determine the significance of the problems and doubts listed here.

An alternative approach is to rely more heavily on market forces to provide the investment decisions. Keck (1980) argues that if firms are required to provide their own finance there will be more thorough and realistic economic assessments and these assessments will be used in decision making; (the optimistic bias apparent in CEGB forecasting will be much less likely). Henderson (1981) also believes strongly in market forces, claiming that a major reason for the initial AGR decision and its continuation despite manifest problems was the centralisation of decision making. The latter leads to emphasis on "secondary goals such as energy self-sufficiency or the development of indigenous technology" (27) which protect any investment no matter how bad the mistakes.

While Henderson may be quite right that centralised decision making has led to the continuation of bad choices based on "pre-economic" concepts (28), it should also be clear that the advice available from a properly conducted SCBA would put those choices back into a true economic framework, or, should the advice be ignored, would highlight the explicitly political nature of the decision.

Rush et al (1977) argue that the government has a legitimate role in making technical decisions but, (in the case of the AGR), had no independent technical advice, as such advice was given by the UKAEA which also had the monopoly of civil R & D. Hence, the government was "lacking the technical or economic grounds on which to question the wisdom of commitment to the AGR ... " (29). Yet since that date the only move towards obtaining such grounds has been the Planning Inquiry; specifically on THORP at Windscale in 1978 and on Sizewell B.

Thus, to date the Planning Inquiry has been forced to perform the function of a SCBA, which it is neither designed nor able to do.

One view is that the Planning Inquiry is a mere ritual to reassure the public over a decision which has already been taken (30). The legalistic approach is criticised for attempting to find a definite answer to problems which may be matters of judgement and for "factualising" political viewpoints. Pearce et al (1979) propose an Energy Policy Commission to review energy policy and hence allow the Planning Inquiry to revert to its original, local function.

SCBA is not a technique designed to realise politically determined objectives but is an economic calculation based on willingness to pay as the measure of benefits, and minimum acceptable payments as the measure of costs. Such a calculation ("wholly distinct from and independent of current political objectives" (31)), provides two essential economic contributions to a political decision. Odell (1980) mentions "national pride" as a reason for continued development of nuclear power (32). Now, as Mishan (1982a) points out, a SCBA can easily be adjusted, using "politico-weights" to favour a nuclear programme originally designed for prestige. But such a process (weighting some benefits higher than others, some costs lower) ceases to be an economic calculation and makes SCBA something it cannot be. A decision on nuclear power must inevitably be political; pressure groups against growth, or centralisation, or the development of "hard" technology must make their opinions felt in the political world. They cannot be represented within the economic calculation by, for example, adjusting the weights attached to some measures of costs or benefits. Some people will inevitably object and the interpersonal comparisons of utility are part of the political nature of the decision. By standing apart from such comparisons the SCBA makes explicit those calculations which the economist is able to make independent of political views. And where calculation is impossible through lack of data or a fundamental inability to attach a price, there remain contingency calculations - "the estimates of a critical magnitude for the spillovers which will just offset the excess benefits of a project that is calculated in disregard of the spillovers" (33).

The risk averse conclusion on energy policy is "COCONUC" - coal conservation and nuclear power. It is seen as strategically important to develop the nuclear component to ensure security of fuel supplies. This risk diversification view is explained by economic history. The scale and complexity of the projects and the likelihood of the free market to be operating on prices which are too short term to give a satisfactory basis for nuclear decisions to be made there imply government intervention. Government has provided R and D funds on a very substantial scale (34) and nuclear projects require government controls on safety, and government sponsored monitoring institutions. There will always remain problems of radioactive waste and proliferation. The final decision has to be a political one, but one which must be influenced by the economic analysis of a SCBA.

NOTES TO CHAPTER I

(1) Electricity Council (1985)

(2) Ibid p.4

(3) Ibid p.9 and p.26

(4) Ibid p.29. The Plan also notes that should a "timely and favourable result to the Sizewell B Inquiry not be obtained, then AGR and coal fired generation will be the main choices"

(5) See HESS and CEGB Statistical Yearbook; discussed in Chapters IV and VI

(6) See annual issues of DUKES discussed in Chapters IV and VI

(7) OCED Steering Committee for Nuclear Energy May 1982; quoted in ATOM 309 July 1982

(8) See, for example, Berndt and Wood (1979), Halvorsen and Ford (1978), Hunt (1984)

(9) See CEGB Annual Report and Accounts (1984/5)

(10) It may be impossible to state clearly the intangible effect. Chapters IV and VI both confront the problem of the current lack of hard scientific knowledge concerning some of these effects - the pathways taken and successive effects of specific pollutants for example.

(11) Seneca and Taussig (1984) p.17

(12) The Net Effective Cost argument in favour of building the PWR at Sizewell (discussed in Chapter VI) leads to a similar conclusion for the UK. The rapid French development of nuclear power (and the slogan tout électrique tout nucléaire) makes it apparent that French planners subscribed to the same argument.

(13) Greenhalgh (1984) p.285

(14) and may also be able to assess that analysis on the same grounds as Greenhalgh (1984) believes safety issues should be judged: is the metholology correct, and have the bodies concerned sufficient resources to undertake the analysis required by their methodology?

(15) See Kneese (1977) and Pearce (1979)

(16) Maxey (1979) p.46

(17) Parker (1978) reported on THORP and is discussed Chapter V; Planning Inquiries in general are considered in Chapter VI.

(18) CEGB Annual Report 1984/5 p.39

(19) Ibid p.38

(20) See Purdue et al (1984), Greenhalgh (1984). An earlier attack on the Inquiry approach is in Pearce et al (1979).

(21) "The key problem facing the electricity supply industry concerns the balance between coal and nuclear sources of generation and the need to switch away from oil" - House of Commons (1981) Vol.I p.19

(22) Ibid p.25

(23) Ibid p.18

(24) Franklin (1985) p.8

(25) Bajay (1980) p.265

(26) Mishan (1982a) p.149

(27) Henderson (1981) p.16

(28) The AGR programme has finally produced reactors which supply power to the grid, but "while in technological terms the first AGRs represented a step forward from the Magnox design, it is now clear, with the benefit of hindsight that the technical, managerial and financial problems were seriously underestimated" CEGB Annual Report 1984/5 para.99.

(29) Rush et al (1977) p.100

(30) See Wynne (1980)

(31) Mishan (1982b) p.41

(32) Very much the type of non-economic argument which Henderson (1981) sees behind nuclear decisions in the UK (and in Henderson (1977) in the case of Concorde also).

(33) Mishan (1982a) p.150

(34) The UK R and D budget in 1977 spent 81% of its funds on nuclear energy, 11% on fossil fuels, 5% on conservation, 2% on non-conventional energy and 2% on other technologies - similar to Germany and Japan but more skewed than the rest of Europe or the USA - Landsberg (1980) Chapter 7.

CHAPTER II

THEORETICAL FOUNDATIONS AND PROPOSED MODEL

II.1 INTRODUCTION

An econometric analysis of the production of electricity in England and Wales (1963/4 to 1982/3) is the subject of chapters II and III. There are four major sections: economic and econometric theory behind the choice of model to be estimated; recent literature using the chosen model in energy economics; the data; and results of the estimation.

The basic assumption is that the production process may be represented by a relationship between output of electricity (Q) and inputs (X_i), summarised by the production function

$$Q = f\ (X_i) \qquad [II-1]$$

The first of the four sections considers the problem of the specific functional form to be chosen to represent the above equation for the purpose of econometric estimation. The form chosen is the transcendental logarithmic function, and a survey of studies using this model to analyse the role of energy in the economy is presented as the second section.

II.2 CHOICE OF FUNCTIONAL FORM

II.2.1 The Production Function and the Elasticity of Substitution

The efficient production of electricity is represented by the production function [II-1]. From this general statement follow three elasticities which together provide the information necessary to summarise the most important characteristics of the production process.

First the elasticity of output with respect to any input: $(\partial Q/\partial X_i)/(Q/X_i)$. By using the elasticity to relate the given input to total output, the measurement is normalised, and so can demonstrate the relative significance of the input. If the industry were perfectly competitive, and operating under constant returns to scale, then this elasticity will be the relative share in the value of output of the particular input.

Second, the elasticity of output with respect to a proportional change in all inputs - whether or not the production function displays (dis)economies of scale.

Third, the elasticity of substitution between inputs. If the production function [II-1] is written for the case of two inputs, labour (L) and capital (K):

$$Q = f(K, L) \qquad [II-2]$$

then the elasticity of substitution is defined to be:

$$\sigma_{LK} = \frac{K/L.d(L/K)}{f_L/f_K.d(f_K/f_L)} \Bigg|_{Q \text{ constant}} \qquad [II-3]$$

where

$f_L = \partial Q/\partial L$ the marginal product of labour

$f_K = \partial Q/\partial K$ the marginal product of capital

Thus [II-3] represents the proportionate change in the ratio of factor inputs due to a proportionate change in the marginal rate of substitution (MRS_{LK}) where

$$MRS_{LK} = dK/dL = (\partial Q/\partial L)/(\partial Q/\partial K) \quad [II\text{-}4]$$

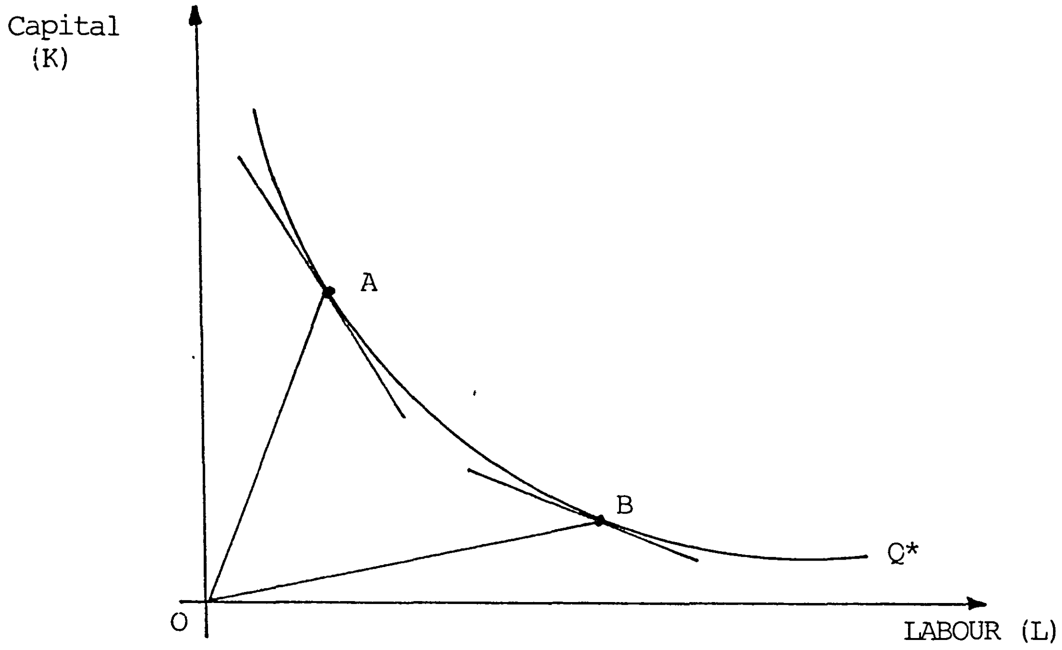
Alternatively:

$$\sigma_{LK} = \frac{d \log (K/L)}{d \log MRS_{LK}} \quad [II\text{-}5]$$

The value of the MRS represents the incremental use of labour (capital) necessary when a small reduction is made in the use of capital (labour).

Since isoquants, in general, are convex to the origin, the value of the MRS must rise as the labour input rises and the capital input declines, along the isoquant. As the process of substitution continues, so that process becomes harder and harder to achieve. The elasticity of substitution is the measure of how fast the MRS increases; for two factors of production it is defined along an isoquant as the elasticity of the factor input ratio with respect to the MRS.

Figure II-1 Elasticity of Substitution



In figure II-1 Q* represents a particular isoquant between labour (L) and capital (K).

A is the initial equilibrium.

If a movement is made from A to B, then d(L/K) represents the increase in the use of L compared with the use of K. The corresponding change in the MRS is given by $d(f_K/f_L)$. The ratio of these two measures, each normalised by being expressed as a proportion, is the elasticity of substitution between the two inputs:

$$\sigma_{LK} = \left. \frac{K/L.d(L/K)}{f_L/f_K.d(f_K/f_L)} \right|_{Q \text{ constant}} \qquad [II-3]$$

$$= \frac{\text{relative change in the gradient of OA to OB}}{\text{relative change in the gradient of tangent A to tangent B}}$$

Because the elasticity of substitution measures the degree to which the two inputs may be substituted for each other (output constant), it is, therefore, a measure of the curvature of the isoquant. It shows the percentage change in the labour to capital ratio following a one per cent change in the marginal rate of substitution of labour for capital (output constant). Clearly the elasticity can take any value between zero and infinity. A zero value implies that the two inputs are combined in fixed proportions and the isoquants take the form shown in figure II-2. A value of infinity for the elasticity of substitution implies that the isoquants would appear as straight lines as in figure II-3.

Figure II-2

Zero Elasticity of Substitution

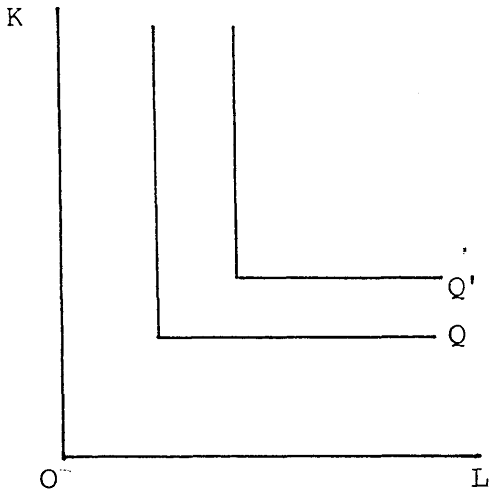
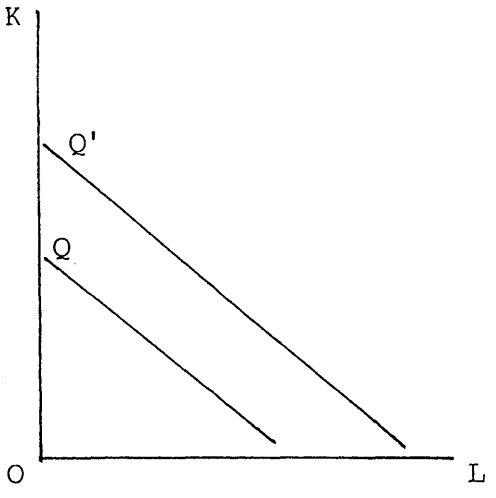


Figure II-3

Infinite Elasticity of Substitution



'High' values for the elasticity of substitution mean that a small change in the MRS produces a wide variation in the capital to labour ratio, and the isoquants will be fairly flat.

If the production function is of the form:

$$Q = f(X_1, \ldots, X_n) \qquad [II\text{-}6]$$

then the partial elasticity of substitution may be defined. Let:

$f_i = \partial f / \partial X_i$

$f_{ij} = \partial^2 f / \partial X_i \partial X_j$

$$F = \begin{vmatrix} 0 & f_1 & f_2 & f_3 & \cdots & f_n \\ f_1 & f_{11} & f_{12} & f_{13} & \cdots & f_{1n} \\ f_2 & f_{21} & f_{22} & f_{23} & \cdots & f_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\ f_n & f_{n1} & f_{n2} & f_{n3} & \cdots & f_{nn} \end{vmatrix}$$

which is the Hessian matrix of second partials of the function f, bordered by the vector of first partials.

F_{ij} = the cofactor of the ijth element in F.

Allen's (1938) definition of the partial elasticity of substitution between X_i and X_j is the normalised response of a change in the price of the X_jth factor on the amount demanded of the X_ith factor, where output is held fixed and where the quantities of all other factors of production are permitted to vary.

$$\sigma_{ij} = \frac{X_1 f_1 + X_2 f_2 + \ldots + X_n f_n}{X_i X_j} \cdot \frac{F_{ij}}{F} \qquad [II\text{-}7]$$

Two functional forms in particular have been widely used in the applied literature concerned with two input (here K and L) production functions; the Cobb-Douglas (CD) and Constant Elasticity of Substitution (CES) functions. The former constrains the elasticity of substitution to be unity:

CD production function: $Q = AL^{\alpha}K^{\beta}$ [II-8]

$$MRS_{LK} = dK/dL = (\partial Q/\partial L)/(\partial Q/\partial K)$$
$$= \alpha K/\beta L \quad [II-9]$$

so $K/L = \beta/\alpha \;.\; MRS_{LK}$

and $\log (K/L) = \log (\beta/\alpha) + \log MRS_{LK}$

Thus, the elasticity of substitution:

$$\sigma_{LK} = \frac{d \log (K/L)}{d \log MRS_{LK}} = 1$$

The two inputs may always be substituted one for the other at this unit elasticity.

The CES production function introduced in Arrow et al (1961)), represents a less stringent restraint on the modelling of production technology, no longer forcing the data to conform to an elasticity of substitution of unity, (which may clearly be wrong, a priori, for some industries).

CES production function: $Q = A\,(\delta K^{-\rho} + (1-\delta)L^{-\rho})^{-v/\rho}$ [II-10]

The elasticity of substitution may now take any positive value:

$$MRS_{LK} = dK/dL = (\partial Q/\partial L)/(\partial Q/\partial K) = ({}^{1-\delta}/_{\delta})(K/L)^{1+\rho} \quad [II-11]$$

$$\sigma_{LK} = \frac{d \log (K/L)}{d \log MRS_{LK}}$$

$$\log MRS = \log ({}^{1-\delta}/_{\delta}) + (1+\rho) \log(K/L)$$

$$\frac{d \log MRS}{d \log (K/L)} = 1 + \rho$$

$$\sigma = \frac{1}{1 + \rho} \qquad [II\text{-}12]$$

Hence ρ is sometimes referred to as the substitution parameter, (Walters (1963; 1968). Note that as $\rho \rightarrow 0$, so the CES production function tends to (and in the limit becomes) CD.

There are, however, drawbacks to the use of the CES production function in empirical work. Although less restrictive than the CD form, it still constrains the elasticity of substitution to be constant at all points.

Second, consider the total cost function which may be derived from the CES production function:

$$TC = (Q/A)^{1/v} (\delta^{\sigma} R^{1-\sigma} + (1-\delta)^{\sigma} W^{1-\sigma})^{1/1-\sigma} \qquad [II\text{-}13]$$

where

TC is total cost

R is the rental on capital

W is the wage rate

$\sigma = 1/1+\rho$

This may not be transformed to a function which is linear in the parameters, (whereas that is accomplished for the CD form by taking logarithms), nor may the CES production function be so transformed. This means that estimation would involve non-linear methods, or using the marginal productivity conditions. Estimation of the CES production function is analysed by Fishelson (1979).

The third problem associated with the use of the CES production function arises when more than two inputs are involved. The CES form restricts all the Allen partial elasticities of substitution to be constant and equal for any pair of inputs and for all points in input space; this constraint rules out the possibility of complementarity between inputs, (as shown by Uzawa (1962), and McFadden (1963)).

Kmenta (1967a), provided an approximation to the CES production function using an equation which is log-linear and thus suitable for the traditional estimation techniques.
Write the CES production function:

$$Q/L = AL^{v-1}\{\delta + (1-\delta)(K/L)^{-\rho}\}^{-v/\rho} \qquad [II-14]$$

and transform into logs:

$$\log(Q/L) = \log A + (v-1)\log L - (^{v}/\rho) \,.\, f(\rho) \qquad [II-15]$$

where

$$f(\rho) = \log\{\delta + (1-\delta)(K/L)^{-\rho}\}$$

The Kmenta approxmation involves a Taylor series expansion of the log of the function around the value $\rho = 0$, and excluding terms of third order and higher. This exclusion is made for two reasons: (i) using a power series in log (K/L) as a vector of regressors would result in a high degree of multicollinearity, and (ii) there are four parameters to be estimated and [II-15] would be overidentified if $n > 2$, so the Taylor series is truncated at $n = 2$ to ensure identification.

$$f(\rho) \cong f(0) - f'(0)\rho + \tfrac{1}{2} f''(0)\rho^2 \qquad [II-16]$$

where

$f(0) = 0$

$f'(0) = -(1-\delta)\log(K/L)$

$f''(0) = \delta(1-\delta)(\log\{K/L\})^2$

Thus

$$f(\rho) \cong -\rho(1-\delta)\ \log(K/L) + \tfrac{1}{2}\rho^2\delta\ (1-\delta)(\log\{K/L\})^2 \qquad [II\text{-}17]$$

Substitution of [II-17] into [II-14] yields the logarithmic approximation to the CES production function:

$$\log\ (Q/L) \cong \log A + (v-1)\log L + v(1-\delta)\log\ (K/L) - \tfrac{1}{2}\rho v\ \delta(1-\delta)(\log\{K/L\})^2 \qquad [II\text{-}18]$$

For estimation [II-18] is written:

$$\log\ (Q/L) = \beta_0 + \beta_1 \log L + \beta_2 \log\ (K/L) + \beta_3\ (\log\{K/L\})^2 \qquad [II\text{-}19]$$

The quality of [II-19] as an approximation to the CES production function has been criticised. As noted above, if $\rho \to 0$ then $\sigma \to 1$, and the CES form reduces to the CD. The closer σ is to unity, the better is the performance of [II-19] as an approximation. In any empirical test if β_3 is not significantly different from zero then [II-19] may be used as evidence for not rejecting the CD production function. However, as σ departs from unity the hypothesis that the 'true' production function is CD is rejected in favour of adopting the CES form with $\rho \neq 0$.

But the latter is not the correct alternative hypothesis. McCarthy (1967) points out that the functional form shown in [II-19] is actually an approximation to a quite general class of functions of which the CES is a special case. The problem lies in the exclusion of the third and higher order terms in the Taylor series expansion, since as σ diverges from unity, these may be expected to be of increasing importance. Ignoring them implies that the 'true' function is CES. Should this not be the case, the estimators will be biased and inconsistent. Thursby and Knox Lovell (1978) use Monte Carlo experiments to show that the estimates of log A and ρ have large bias and mean squared error except when the true value of ρ is close to zero. When σ diverges from unity ($\rho \neq 0$) the bias in all parameter estimates increases. The bias is not uniformly upward or downward, but varies in their experiments.

Kmenta's (1967b) reply to McCarthy was that part of the price of using an approximation rather than the true function was the loss of some precision and power of statistical tests of significance. The important (empirical) points remained (i) that the error of approximation remained small unless extreme values of σ were combined with extreme values of input ratios, and

(ii) that if [II-19] served as a good approximation to the CES production function then it does not matter that it also approximates a wider class of functions.

Griliches and Ringstad (1971) used the Kmenta approximation although noting further estimation problems. The coefficient β_3 in [II-19] is equal to $\frac{1}{2}\rho\, v\delta(1-\delta)$ where δ and $(1-\delta)$ are both less than one. This makes the absolute value of β_3 likely to be low and requires large samples with substantial dispersion in the K/L ratios for confidence in the sign and magnitude of the estimate of β_3. Also the Kmenta approximation is not a constant elasticity form and the resulting coefficient and parameter estimates are not invariant with respect to units of measurement. This can be overcome (i) by redefining K and L so that their geometric averages are equal in the sample and $\overline{\log(K/L)} = 0$, or

(ii) by dividing each variable by its sample mean.

The Kmenta approximation is homothetic and thus σ is dependent only on the input ratio. This can be tested by expanding the square term to give:

$$\log(Q/L) = \beta_0 + \beta_1 \log L + \beta_2 \log (K/L) + \beta_{31}(\log K)^2 - 2\beta_{32}(\log K.\log L) + \beta_{33}(\log L)^2 \qquad [II-20]$$

The requirement for homotheticity is that:

$$\beta_{31} = \beta_{32} = \beta_{33} = \beta_3$$

and this may be tested for in the standard manner. Rejection of homotheticity may imply acceptance of a more general and non homothetic polynomial form.

II.2.2 Homogeneity and Homotheticity in Production Functions - see note (1)

II.2.3 The Transcendental Logarithmic Model

The problems surrounding the use of the CD and CES functional forms in empirical work are essentially due to their 'inflexibility'. That is, their adoption imposes fairly significant constraints at the outset of the investigation. A preferable approach would be to impose some of these constraints on a more general model in the form of testable hypotheses which may be accepted or rejected. The 1970's saw the introduction of more flexible functional forms which allow precisely this methodological approach.

In 1971 Christensen, Jorgensen and Lau introduced the transcendental logarithmic production function. This is a transcendental function of the logarithms of its arguments; the production function can have an arbitrary number of inputs and none of the restrictions referred to above apply. The translog form had already been published independently in three sources. Kmenta's approximation to the CES function (1967) was in fact a special case, representing a homogeneous translog production function. In 1971 Griliches and Ringstad used the Kmenta approximation, and Sargan developed the translog form in 1971 also.

II.2.4 Derivation of the Translog Estimating Equations

The translog production function is nonhomothetic, nonhomogeneous and places no restrictions on the elasticities of substitution, which may vary at each data point. Its choice as the basic functional form allows tests of the CD and CES forms to be undertaken by placing testable restrictions on the translog parameters. It is assumed that every establishment has the same production function, but in the translog form, because the elasticity of substitution is different at every data point, (in cross section studies) size of the establishment will affect the substitution properties of the technology. This means that a U shaped cost curve (for example) may be discernable as scale economies are allowed to vary with output.

The use of either the CD or CES form would mean that the production or the cost function could be used interchangeably; each would generate the same results as they are self-dual. This is not the case with the translog functional form, because, unlike the CD and CES forms, it is not strongly separable in its arguments (see later discussion on separability). Thus in general, different results will occur according to the choice of production or cost function as the model.

Thus, if the translog production function is used to examine substitution possibilities in a manufacturing industry under the maintained hypothesis that it is an exact representation of the 'true' production function, then it is not also possible to use a translog cost function as an exact representation of the 'true' dual cost function in the relevant range, (see Burgess 1975).

Assume a production function of the general form:

$$\log Q = \log A + F(\log K, \log L, \log M) \qquad [II\text{-}21]$$

where

Q is output

A is an index of technological change

K is capital services

L is labour services

M is intermediate material inputs

Assume that this function demonstrates both constant returns to scale and Hicks neutral technical change. (The latter assumption ensures that technological change affects all factors of production equally.) Under these conditions [II-21] can be rewritten:

$$\log Q - \log A = F \qquad [II\text{-}22]$$

and F is evaluated by a second order Taylor series approximation around the point at which all inputs are unity:

$$\begin{aligned} F = F(0) &+ \frac{\partial F}{\partial \log K} . \log K + \frac{\partial F}{\partial \log L} . \log L + \frac{\partial F}{\partial \log M} . \log M \\ &+ \tfrac{1}{2} \frac{\partial^2 F}{\partial (\log K)^2} .(\log K)^2 + \tfrac{1}{2} \frac{\partial^2 F}{\partial (\log L)^2} .(\log L)^2 + \tfrac{1}{2} \frac{\partial^2 F}{\partial (\log M)^2} .(\log M)^2 \\ &+ \tfrac{1}{2} \frac{\partial^2 F}{\partial \log K \, \partial \log L} .\log K.\log L + \tfrac{1}{2} \frac{\partial^2 F}{\partial \log L \, \partial \log K} .\log L.\mathrm{Log}\, K \\ &+ \tfrac{1}{2} \frac{\partial^2 F}{\partial \log K \, \partial \log M} .\log K.\log M + \tfrac{1}{2} \frac{\partial^2 F}{\partial \log M \, \partial \log K} .\log M.\mathrm{Log}\, K \\ &+ \tfrac{1}{2} \frac{\partial^2 F}{\partial \log L \, \partial \log M} .\log L.\log M + \tfrac{1}{2} \frac{\partial^2 F}{\partial \log M \, \partial \log L} .\log M.\mathrm{Log}\, L \qquad [II\text{-}23] \end{aligned}$$

This is written more succinctly as:

$$F = F(0) + \sum_i \frac{\partial F}{\partial \log X_i} \log X_i + \sum_i \sum_j \frac{\partial^2 F}{\partial \log X_i \ \partial \log X_j} \log X_i . \log X_j \qquad [II-24]$$

where

X_i and X_j are any two inputs

Now substitute parameters for the first and second order derivatives in [II-23] or [II-24]:

$$\begin{aligned} \log Q = {} & \log a + a_k \log K + a_l \log L + a_m \log M + \tfrac{1}{2} \ b_{kk} (\log K) \\ & + \tfrac{1}{2} \ b_{ll} (\log L) + \tfrac{1}{2} \ b_{mm} (\log M) + b_{kl} \log K . \log L \\ & + b_{lm} \log L . \log M + b_{km} \log K . \log M \qquad [II-25] \end{aligned}$$

or:

$$\log Q = a_0 + \sum_i a_i \log X_i + \tfrac{1}{2} \sum_{ij}\sum b_{ij} \log X_i . \log X_j \qquad [II-26]$$

where

i, j represent K, L, M

b_{ij} is a symmetric matrix

Similarly a cost function can be derived. Assume the general form is:

$$\log C = G(\log Pk, \log Pl, \log Pm) \qquad [II-27]$$

where

C is total cost

Pk is the rental price of capital

Pl is the wage rate

Pm is the price of intermediate inputs

Here G is evaluated by a second order Taylor series expansion around the point where all inputs are unity, and the same procedure as above will yield:

$$\log C = \alpha_0 + \sum_i \alpha_i \log P_i + \tfrac{1}{2} \sum_{ij}\sum \beta_{ij} \log P_i . \log P_j \qquad [II-28]$$

where

P_i and P_j represent the prices of capital, labour and materials

β_{ij} is a symmetric matrix.

At the most general level the cost function has the form:

$$C = c(Q, P) \tag{II-29}$$

representing the minimum cost of attaining output Q at prices Pi. Taking the partial derivatives of this cost function with respect to the prices yields (by Shepherd's lemma (see Shepherd [1953] and [1970])), the Hicksian demand functions:

$$\partial c(Q, P)/\partial P_i = h_i(Q, P) = X_i \tag{II-30}$$

showing how input demands change with prices, output held constant. That is, Shepherd's lemma demonstrates that partial differentiation yields the cost-minimising demands underlying any known cost function. Expressed in logarithmic form for the translog function, Shepherd's lemma is:

$$\frac{\partial \log C}{\partial \log P_i} = \frac{P_i X_i}{P.\ G} = S_i \tag{II-31}$$

where

P_i is the price of the ith input

P is the general price index

S_i is the cost share of the ith input

This process of taking logarithmic partial derivatives yields the following set of equations for the cost shares of the inputs:

$$\left.\begin{aligned} Sk &= a_k + b_{kk} \log K + b_{kl} \log L + b_{km} \log M \\ Sl &= a_l + b_{lk} \log K + b_{ll} \log L + b_{lm} \log M \\ Sm &= a_m + b_{mk} \log K + b_{ml} \log L + b_{mm} \log M \end{aligned}\right\} \tag{II-32}$$

(Equations [II-32] are the result of differentiating [II-28] with respect to log P_i).

II.2.5 Restrictions on the Equations

Restrictions are imposed on the values of the parameters to guarantee that the cost share equations correspond to a well-behaved production (or cost) function consistent with neoclassical theory.

(i) The adding up criterion:

Since the cost shares must sum to unity:

$$S_k + S_l + S_m = 1$$

therefore

$$a_k + a_l + a_m + (b_{kk} + b_{lk} + b_{mk}) \log Pk + (b_{kl} + b_{ll} + b_{ml}) \log L + (b_{km} + b_{lm} + b_{mm}) \log M = 1$$

and the restrictions imposed to achieve this are:

$$a_k + a_l + a_m = 1 \qquad [II-33]$$

$$\left.\begin{aligned} b_{kk} + b_{lk} + b_{mk} &= 0 \\ b_{kl} + b_{ll} + b_{ml} &= 0 \\ b_{km} + b_{lm} + b_{mm} &= 0 \end{aligned}\right\} \qquad [II-34]$$

This criterion satisfies the condition that a well-behaved cost function is linear homogeneous in factor prices. For a fixed output level total cost must increase proportionally when all prices increase proportionally

(ii) Slutsky Symmetry:

$$b_{ij} = b_{ji} \qquad i,\ j = K,\ L,\ M \qquad [II-35]$$

the b_{ij} parameters were derived from partial differentiation of the cost function [II-29]: $\partial c(Q, P)/\partial P_i = h_i$ [II-30]

therefore

$$\frac{\partial h_i}{\partial P_j} = \frac{\partial^2 c}{\partial P_j \partial P_i}$$

and

$$\frac{\partial h_j}{\partial P_i} = \frac{\partial^2 c}{\partial P_i \partial P_j}$$

Since the order of the double differentiation does not matter, then:

$$\frac{\partial h_i}{\partial P_j} = \frac{\partial h_j}{\partial P_i} \quad \text{or } b_{ij} = b_{ji} \quad \text{as above} \qquad [II-33]$$

When restrictions [II-33], [II-34] and [II-35] are imposed, the translog cost function is linear homogeneous.

Further conditions of 'well-behavedness' to be met are:

(iii) monotonicity: all fitted cost shares should be positive

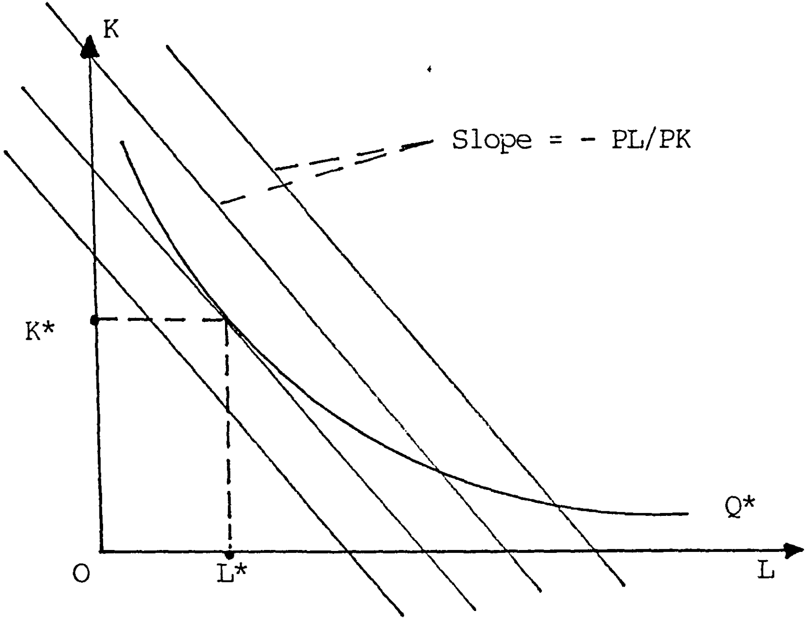
(iv) negativity, (or concavity of the function): this implies a negative definite bordered Hessian matrix of first and second partial derivatives.

II.3 EMPIRICAL ANALYSIS

II.3.1 Introduction

In his 1963 paper, Nerlove estimated returns to scale in electricity supply in the USA using a Cobb-Douglas production function and the cost function derived from it. Lying behind the procedure is the assumption that the firm may be viewed as minimising cost subject to the production function, given factor prices. The firm is able neither to vary output at will nor to store power, and must supply all the power demanded at regulated prices. Thus output may be treated as exogenous. Because the electricity producer buys factor inputs in what are assumed to be competitive markets, factor prices are also taken to be exogenous. Thus the input levels are endogenous and the cost minimising firm optimises by selecting the most efficient input mix (figure II.5).

Figure II-5 Cost Minimisation



In figure II-5 the production function is assumed to be

$$Q = f(K, L)$$

and the prices of the capital (K) and labour (L) inputs are given as Pk and Pl. This factor price ratio is shown as the set of parallel lines having slope -Pl/Pk. Output is exogenously determined and is set at Q*, represented on the diagram by isoquant Q*. To minimise cost the firm will choose that set of inputs determined by the tangency between the isoquant Q* and a factor price ratio curve, in effect the firm is selecting the lowest possible price ratio curve consistent with meeting the output determined for it at Q*. This results in capital and labour inputs of K* and L* as the optimum factor mix.

The UK conditions are inevitably different as electric power supply is a nationalised industry and the US studies concentrate on private enterprise power plants. Nevertheless the assumptions which permit the cost-minimising model to be adopted for the USA have similar implications for the UK. With minor exceptions power is non-storable and is supplied to meet demand. (To some extent the load pattern on the electricity industry is smoothed by charging higher prices at peak periods). The pricing structure may not be altered readily, but is subject to government agreement within the framework of controls over the nationalised industries as a whole. Thus total revenue is, in large part, predetermined. The exogeneity of factor prices may also be assumed for the UK. The Central and Area generating boards compete for labour, and the labour input is priced by annual negotiation with the major unions. It is not subject to change by any individual power station or area board. The variability of fuel prices may be taken to depend on market conditions. The residual (or heavy) fuel oil that is burnt in power stations has traditionally been regarded as almost a waste product of the refining process, of value only to an industry of sufficient size to afford the capital needed to handle it. In the past the price of residual fuel may not have fully reflected a market process, however, since 1973/74 refineries have been under pressure to increase the 'take' from a given input of crude oil. One result has been a reduction in the quantity of residual fuel oil being produced, and as dramatic an increase in its price as has been the case for oil products in general.

Coal prices are linked to miners' wages and to the degree to which the government-imposed financial targets are met by the National Coal Board (NCB). The Central Electricity Generating Board (CEGB) and the NCB have reached agreement on the annual amount of coal to be consumed by the former, and the price to be charged. This agreement leaves little room for the CEGB to import coal, although some steam coal is bought from the USA and Australia, giving an international price element to the contract between the CEGB and the NCB (2).

Finally there is a world market for uranium, which, although depressed in recent years, is clearly not within the control of the CEGB. In addition, the various processes that the uranium must go through both before and after burning in the reactor are not undertaken by the CEGB itself, and have prices which reflect international as well as domestic conditions.

As a nationalised industry the CEGB does not raise capital through any of the normal competitive channels, but through the government. This has not been subject to the same profit-constraints. However the guidelines for control of the nationalised industries have shown awareness of the (possible) problem of lack of incentives and resource misallocation. For example, an unduly low government determined interest rate could lead to excess investment; a tendency which would be strengthened by the existence of increasing returns to scale allied to a steady growth in demand. (3) Certainly, the CEGB has been criticised for allowing the creation of substantial excess capacity. As a first approximation it may be assumed that the Test Discount Rate followed by the 5% overall required rate of return on capital have proved satisfactory in creating a market environment for the capital investment decisions of the CEGB.

If the assumptions Nerlove used to allow the US industry to be modelled are transferable to UK conditions, then the CEGB may be viewed as a cost minimising enterprise, making decisions to determine the optimum level of inputs.

II.3.2 Objectives

1. To analyse the role of the fuel inputs to the production of electricity (taken here to be coal, oil and uranium); to estimate the elasticities of substutition between them and the own- and cross-price elasticities of demand, and, hence, discuss the opportunities for inter-fuel substitution.

2. To estimate the partial elasticities of substitution between the capital, labour and fuel inputs - and their own - and cross-price elasticities of demand for each input. This provides the material for discussion of the substitution possibilities between two inputs.

II.3.3 The Model

The production function for electricity is written in the most general form as:

$$Q = f(K, L, F_i) \qquad [II-36]$$

where

Q is output of electricity

K is services of capital

L is services of labour

F_i are the fuel inputs

Assume that the function [II-36] is weakly separable in the K, L, F aggregates so that it may be written:

$$Q = f\{K(K_1, \ldots, K_k), L(L_1, \ldots, L_L), F(F_1, \ldots, F_f)\} \qquad [II-37]$$

where

$K(K_1, \ldots, K_k)$ are aggregator functions allowing K, L and F
$L(L_1, \ldots, L_L)$ } to be written as the aggregate inputs of capital
$F(F_1, \ldots, F_f)$ labour and fuels.

II.3.4 Separability see note (4)

The assumption that the K, L, F inputs are weakly separable may appear to be contradicted in the case of the particular example used here, but it is not in fact too restrictive. Suppose the capital input is furnaces and turbine generators; two of the fuel inputs are coal and oil. Since the generators are fuel-specific, the separability argument may appear not to hold. But capital is measured in (constant) money terms, which implies that as long as the coal burning generator and the oil burning generator result in the same constant money measure then the condition for separability will be satisfied.

The industry is assumed to act as if it were competitive, and to face exogenous factor prices; thus there is a standard constrained maximisation problem. In addition the electricity supply industry is further constrained by its legal requirement to meet all load demands made on it. Thus factor prices and the output level are exogenously determined.

Duality theory can be used to show that, given cost-minimising behaviour the factor input demand results derived from analysis of the production function may also be derived from the dual cost function:

$$C = c(Pk, Pl, Pf, Q) \qquad [II-39]$$

This relates the minimum cost of producing an output Q to the input prices, technology and the output level.

Given that the production function is weakly separable in the K, L, F inputs, then the corresponding dual cost function has the same partition in input prices. This means that the input price aggregates are positive strictly quasiconcave homothetic functions of only the elements in each subset:

$$P^m = g_m\,(Pi) \qquad \text{for all i belonging to Nm}$$
$$m = 1 \ldots r \qquad [II-40]$$

Further, assuming that the fm and gm functions are linear homogeneous guarantees that the product of the aggregate price and quantity indices equals the total cost of the components.

The economic relevance of the weak separability assumption is that the marginal rate of substitution between individual fuels is independent of the quantities of capital and labour. This allows the use of aggregate price indices for K, L, F.

The assumption of taking the K, L, F aggregates to be homothetic in their components is necessary and sufficient for the model to approximate an underlying two-stage optimisation procedure:

(i) optimise the mix of fuels that makes up the overall fuel input,

(ii) then optimise the quantities of capital, labour and fuel.

The cost function under consideration now becomes:

$$C = C\{c(Pk, Pl, Pf(Pc, Po, Pu), Q)\} \qquad [II-41]$$

where

Pf is an aggregate price index for fuel, representing an aggregator function for the fuel prices Pc, Po, Pu (coal, oil, uranium). Since it is homothetic it does not include the total quantity of energy as one of its arguments.

II.3.5 <u>The METHOD</u> will follow the two stage optimisation procedure:

1. Represent the price of fuel by an appropriately chosen homothetic cost function with constant returns to scale. This allows estimation of the own- and cross-price elasticities of demand, and partial elasticities of substitution between the three fuels. Since this is an aggregator function over the fuel prices it provides an instrumental variable for the price of fuel.

2. Represent the cost of electricity output by a nonhomothetic cost function and estimate the partial elasticities of substitution, own- and cross-price elasticities for capital, labour and fuel.

II.3.6 <u>The FUNCTIONAL FORM</u> chosen is the translog cost function, which represents a second order approximation to any arbitrary cost function. There is a series of benefits following from this choice. The translog function is nonhomothetic, nonhomogeneous and places no restrictions on the elasticities of substitution, which may vary at each data point. In addition its choice as the basic functional form allows tests of the CD and CES forms to be included by placing testable restrictions on the translog parameters. It is assumed that every establishment has the same production function, but in the translog form because the elasticity of substitution is different at every data point the size of the establishment will affect the substitution properties of the technology, meaning that a U shaped cost curve would be derived if scale economies varied with output.

The use of either the CD or CES form would mean that the production or cost function could be used interchangeably and each would generate the same results as they are self dual. This is not the case with the translog form because it is not strongly separable in its arguments, and different results will occur according to the choice of production or cost function as the maintained hypothesis. The model used here is a cost function, chosen because the assumption of cost minimisation and exogenous factor prices is more realistic than assuming exogenous input quantities.

The cost share equations derived from the translog form of the fuel cost function are:

$$\left.\begin{aligned} S_c &= a_c + b_{cc} \log Pc + b_{co} \log Po + b_{cu} \log Pu \\ S_o &= a_o + b_{oc} \log Pc + b_{oo} \log Po + b_{ou} \log Pu \\ S_u &= a_u + b_{uc} \log Pc + b_{uo} \log Po + b_{uu} \log Pu \end{aligned}\right\} \qquad [\text{II-42}]$$

II.3.7 ERRORS in optimising behaviour

If the translog cost function is assumed to be an exact representation of the 'true' cost function then any deviations of the cost shares from the logarithmic marginal costs may be assumed to be the result of errors in the cost-minimising behaviour. Thus an additive disturbance term may be included in each equation to give an stochastic specification.

Given that the cost shares sum to unity, the covariance matrix of disturbances for all equations would be singular; thus the estimation procedure is to drop one equation and estimate the remaining two. The parameter estimates for any one of the three equations can be derived from the estimates of the other two, because of the adding up criterion. The estimates will be identical regardless of the two equations chosen for estimation provided an iterative simultaneous estimation technique, or maximum likelihood methods are used.

II.3.8 Quantification Procedure

The assumption of linear homnogeneity is incorporated by moving from:

$$S_c \underset{.}{=} a_c + b_{cc} \log Pc + b_{co} \log Po + b_{cu} \log Pu + e_c$$

to

$$S_c \underset{.}{=} a_c + b_{cc} \log Pc + b_{co} \log Po - (b_{cc} + b_{co}) \log Pu + e_c \qquad [II-43]$$

so that the constraint that:

$$b_{cc} + b_{co} + b_{cu} \underset{.}{=} 0$$

is included. Thus the two equations to be estimated to test for linear homogeneity are:

$$\left.\begin{aligned} S_c &\underset{.}{=} a_c + b_{cc} \log(Pc/Pu) + b_{co} \log(Po/Pu) + e_c \\ S_o &\underset{.}{=} a_o + b_{oc} \log(Pc/Pu) + b_{oo} \log(Po/Pu) + e_o \end{aligned}\right\} \qquad [II-44]$$

The test for symmetry involves constraining b_{co} to equal b_{oc}. This is achieved by stacking equations [II-44] and using dummy variables:

$$\begin{bmatrix} S_c \\ S_o \end{bmatrix} \underset{.}{=} a_c \begin{bmatrix} 1 \\ 0 \end{bmatrix} + a_o \begin{bmatrix} 0 \\ 1 \end{bmatrix} + b_{cc} \begin{bmatrix} \log(Pc/Pu) \\ 0 \end{bmatrix} +$$

$$b_{oo} \begin{bmatrix} 0 \\ \log(Po/Pu) \end{bmatrix} + b_{co} \begin{bmatrix} \log(Po/Pu) \\ \log(Pc/Pu) \end{bmatrix} \qquad [II-45]$$

This is a process in which the tests are made sequentially, since symmetry is nested in the homogeneity hypothesis.

The translog functional form is sufficiently general to permit the partial elasticities of substitution between pairs of inputs to vary from year to year and from one pair of factors to another. Allen's (1938) definition of the elasticity of substitution between factors i and j is the normalised response of a change in the price of the jth factor on the amount demanded of the ith factor, output constant, but other factors variable. For the translog case this is shown by Uzawa (1962) to be:

$$\sigma_{ij} = \frac{b_{ij} + S_i.S_j}{S_i.S_j} \qquad [II-46]$$

while the price elasticities of demand for factor inputs may be calculated as:

$$\eta_{ij} = S_j.\ \sigma_{ij} \qquad [II-47]$$

and

$$\sigma_{ii} = \frac{b_{ii} + (S_i^2 - S_i)}{S_i^2} \qquad [II-48]$$

Once the fuel subsystem has been estimated it is possible to return to the initial fuel cost equation and to use it to produce an aggregate price index for fuel as a whole.

Thus the procedure begins with:

$$Q = f\ (K,\ L,\ F_i) \qquad [II-36]$$

and assumes (imposes) homothetic weak separability in fuel so that [II-36] may be rewritten:

$$Q = f\ \{\ K,\ L,\ F(F_i,\ \ldots,\ F_n)\} \qquad [II-49]$$

where F becomes the total fuel measure and is an appropriately chosen homothetic aggregator function. This will not be a simple sum of the BTU equivalents of the fuels unless the fuels are perfect substitutes or complements in production.

From duality theory it can be shown that the production process may be analysed using the cost function dual to [II-36]:

$$C = C\{ Pk, Pl, Pf(Pf_1, \ldots, Pf_n), Q\} \qquad [II-50]$$

where

Pf is an aggregator function and so represents an aggregate price index. Similarly this will not be a simple weighted average of the individual fuel prices unless the fuels are perfect substitutes or complements. Thus there remains the problem of the precise method of aggregating the individual fuel prices into the overall fuel price index. Fuss (1977) points out that Divisia aggregation is common in empirical studies which use the translog production function. He then goes on to show that if a translog cost function is chosen as the aggregator function relating the aggregate price index to the component prices, then this is an approximation to using the true continuous Divisia index. That is, the Divisia index is exact for the translog cost function in that it retrieves the actual values of that function. Since the translog cost function is an approximation to the unknown true cost function, it will also be an approximate index.

System estimation of [II-45] has generated values for b_{cc}, b_{co}, b_{oo}, and so on. The price index for fuel is given by:

$$\log Pf = a_o + \sum_i a_i \log Pf_i + \sum_{ij}\sum b_{ij} \log Pf_i . \log Pf_j \qquad [II-51]$$

and the parameter estimates are now substituted into this fuel price aggregator equation. The parameter a_o is unobservable and is set so that the price of fuel is equal to one in the base year. With the data series on fuel prices the price index for the remainder of the time period can be calculated using [II-51]. This now serves as an instrumental variable in the estimation of the overall cost function:

$$C = c(Pk, Pl, \hat{P}f, Q) \qquad [II-52]$$

which in translog form is:

$$\log C = \log a + \sum_{i} a_i \log Pi + aq \log Q + \tfrac{1}{2} \sum_{ij}\sum c_{ij} \log Pi . \log Pj$$

$$+ \sum_{i} c_{iq} \log Q . \log Pi + \tfrac{1}{2} \quad c_{qq} (\log Q)^2 \qquad [II-53]$$

which yields the factor share equations:

$$S_i = a_i + b_{qi} \log Q + \sum_{i} c_{ij} \log Pj \qquad [II-54]$$

where i and j represent capital labour and fuel.

$\hat{P}f$ is the instrumental variable using all prior information

(Conceptually all other inputs can be treated in this manner, but the construction of the required submodels will probably be prevented by lack of data).

Thus [II-54] represents three equations of which two are estimated. As before the share equations are estimated in stages so that successive additional parameter restrictions may be imposed and tested. The full set of equations and restrictions are:

$$S_k = a_k + b_{qk} \log Q + c_{kk} \log Pk + c_{kl} \log Pl + c_{kf} \log Pf + e_k$$
$$S_l = a_l + b_{ql} \log Q + c_{lk} \log Pk + c_{ll} \log Pl + c_{lf} \log Pf + e_l$$
$$S_f = a_f + b_{qf} \log Q + c_{fk} \log Pk + c_{fl} \log Pl + c_{ff} \log Pf + e_f$$

[II-55]

Identifiability requires $a_k + a_l + a_f = 1$

Homotheticity requires $b_{qi} = 0$

Symmetry requires $c_{ij} = c_{ji}$

Imposing homotheticity/homogeneity leads to estimation of:

$$S_k = a_k + c_{kk} \log(Pk/Pf) + c_{kl} \log(Pl/Pf) + e_k$$
$$S_l = a_l + c_{lk} \log(Pk/Pf) + c_{ll} \log(Pl/Pf) + e_l \qquad [II-56]$$

In order to impose symmetry directly, the equations [II-56] may be stacked and estimated as:

$$\begin{bmatrix} S_k \\ S_l \end{bmatrix} = a_k \begin{bmatrix} 1 \\ 0 \end{bmatrix} + a_l \begin{bmatrix} 0 \\ 1 \end{bmatrix} + c_{kk} \begin{bmatrix} \log(Pk/Pf) \\ 0 \end{bmatrix} + c_{ll} \begin{bmatrix} 0 \\ \log(Pl/Pf) \end{bmatrix} + c_{lk} \begin{bmatrix} \log(Pl/Pf) \\ \log(Pk/Pf) \end{bmatrix} + \begin{bmatrix} e_k \\ e_l \end{bmatrix} \qquad [II\text{-}56]$$

II.4 THE TRANSLOG MODEL IN ENERGY ECONOMICS LITERATURE

The transcendental logarithmic production and price possibility frontiers were introduced to the literature by Christensen, Jorgensen and Lau in Econometrica 1971. The same year saw the independent publication of work specifically concerned with production functions by Griliches and Ringstad (1971) and Sargan (1971). The latter works both used the translog production function, which represents a special case of the Christensen-Jorgensen-Lau (C-J-L) translog production possibility frontier. Griliches and Ringstad were drawing on the 1967 publication by Kmenta,which presented a means of approximating the constant elasticity of substitution production function (which cannot, directly, be made linear for estimation purposes). Kmenta's approximation took the form of a homogeneous translog production function.

In 1973 C-J-L published "Transcendental Logarithmic Production Frontiers" in which they had three stated objectives. One was "to exploit the duality between prices and quantities in the theory of production"; here they are referring to earlier work by Samuelson (1953/54) and Shepherd (1953; 1970) which established that the equilibrium production conditions under which relative prices are a function of relative product and factor intensities implied an equivalent set of equilibrium conditions under which relative product and factor intensities are functions of relative prices. The equilibrium can be analysed either through the production possibility frontier (and the necessary conditions for producer equilibrium), or through the price possibility frontier (and the conditions determining product and factor intensities).

The second objective was "to test the theory of production without imposing the assumptions of additivity and homogeneity as part of the maintained hypothesis". In this they are explicitly rejecting the use of the CES production function, whose application to the cases of more than one output or more than two inputs is highly restricting, (in particular, denying the possibility of complementarity between inputs). The C-J-L conclusion is that "the assumption of commodity-wise additivity" (by which they mean additive or strong separability) "that underlies the CES production function is unsuitable as a basis for representing a production possibility frontier with several outputs and several inputs".

This conclusion is strengthened by the results derived from the third objective: to undertake "empirical tests of the theory of production, based on time series data for the United States private domestic economy for 1929 - 1969". Here the "empirical results are consistent with a very extensive set of restrictions implied by the theory of production. Proceeding conditionally on the validity of the theory of production, our empirical results are inconsistent with restrictions on the form of the production function implied by the assumption of additivity".

The C-J-L paper makes a strong case for the superiority of flexible functional forms in empirical work. This is partly because their results indicate that the CES model is rejected for US production data, but also on methodological grounds. A general model can be estimated, and a series of restrictions imposed on it; the acceptability of the restrictions is then subject to the standard test procedures. If, for example, a production function study should result in the acceptance of a restricted model which is CES in form then the value of the study lies precisely in that it has avoided imposing that CES form on the data at the outset.

Berndt and Christensen (1973) were concerned with this problem. They refer to Solow (1955/56). In this article, Solow takes the example of a production function with three inputs, (two capital inputs, one labour input). He shows that provided the two capital inputs are functionally separable from the labour input, then there will exist a consistent aggregate capital price (or quantity) index. The problem being highlighted is one of aggregation, and Solow's contribution is to show that separability is a necessary condition for the existence of aggregate indices.

Berndt and Christensen (1973) point to the drawback involved in using CD or CES functions which are strongly separable. Using a strongly separable function avoids the aggregation problem, by simply assuming that the necessary conditions are satisfied. However the translog function is not strongly separable, but may be made so by (testable) restrictions. This makes it a preferable empirical starting point. Berndt and Christensen go on to develop the relevant tests, firstly for global separability. If this is satisfied then all types of separability are accepted. If the test shows global separability is rejected then, in the context of a three input production function with inputs K L E, Berndt and Christensen develop tests for separability: (K L) from E

(K E) from L

(L E) from K

The theoretical work is then used in a test of the validity of developing an aggregate index of equipment and structures in US manufacturing 1929 - 1968.

Denny and May (1977) are also concerned with the separability restriction. They note that Statistics Canada uses a real value added function to measure the outputs of subsectors of the Canadian economy. This approach is based on the following derivation:

For any subsector of the economy there is a production function of the form:

$$Q = f(K, L, M) \tag{II-4-1}$$

where

Q is gross output in real terms

K is capital

L is labour

M is intermediate input services

If K and L are weakly separable from M then [II-4-1] may be written:

$$Q = f\{h(K, L), M\} \tag{II-4-2}$$

The (linear homogeneous) function h(K, L) is a measure of real value added, and [II-4-2] is written:

$$Q = f(VQ, M) \tag{II-4-3}$$

where

VQ is real value added

Measuring real value added in this manner implies that the assumption that the production technology is separable between the primary inputs and the materials purchased is being used. Denny and May (1979) use the translog functional form as it allows the separability restriction to be tested rather than imposed as a maintained hypothesis. Their results reject separability (and thus deny the assumption of the existence of a real value added function).

Burgess (1975) also deals with theoretical/methodological problems. In this case the problems are concerned specifically with the use of the translog functional form. The flexibility of the translog form allows the Allen partial elasticities of substitution between pairs of inputs to vary at each data point, whereas a strongly separable production function would constrain these elasticities to be constant. However precisely because the translog form is not strongly separable, it is not self-dual. This means that the choice between using a production function or a cost function is no longer arbitrary. Burgess refers to Berndt and Christensen (1973) whose empirical work uses a translog production function under the maintained hypothesis that this is an exact representation of the (unknown) "true" production function over the relevant range. In taking this position Burgess notes that Berndt and Christensen rule out the possibility that the translog form could represent exactly the "true" dual cost function over the same range of data. If empirical results are shown to be sensitive to the choice of maintained hypothesis - that is, if results differ significantly when derived from a production function model than when derived from a cost function model, - then those results must be viewed with some doubt, unless there is some strong a priori reason for favouring the use of one maintained hypothesis over another.

One desirable feature of the translog form noted above has been that it is more general than the CES, but may be rendered equivalent to it by testable parameter restrictions. But for the problem that Burgess is confronting, there is no more general model which may be reduced to the translog specification, other than the hypothesis that the "technology is approximately represented by a translog function rather than exactly represented by it". If the representation is approximate then the appropriate solution is to estimate the production function (or cost function) simultaneously with the factor share equations.

Burgess analyses the problem by fitting a translog production function and a translog cost function to the same set of data. He concludes that "mild changes in our maintained hypotheses may lead to dramatic changes in our inferences about economic events". He finds that the Allen partial elasticities of substitution derived from the production function model are "very different" from those resulting from the cost function model. This difference remains even when it is assumed that the production and cost functions are only approximations to the "true" technology, rather than exact representations of it.

Griffin (1977a) analyses the benefits of using the translog model in electric power generation and he continues this analysis in Griffin (1977b) which is concerned with inter-fuel substitution in the electricity industries of twenty OECD countries for five year intervals, 1955 - 1969. He uses duality theory to move from a production function:

$$E = E(K, L, QC, QG, QO, t) \qquad [II-4-4]$$

where

E is output of electricity

K is services of capital

L is services of labour

QC } { coal
are the
QG } { gas
energy inputs
QO } { fuel oil

t is technical change

to a cost function:

$$C = C(PK, PL, PC, PG, PO, t, E) \qquad [II\text{-}4\text{-}5]$$

where

C is total cost

P represents the price of each input.

Griffin now assumes that coal, gas and fuel oil make up a separable and homogeneous energy aggregate so that [II-4-5] may be written:

$$C = C\{PK, PL, f(PC, PG, PO), t, E\} \qquad [II\text{-}4\text{-}6]$$

$$= C(PK, PL, PF, t, E) \qquad [II\text{-}4\text{-}7]$$

where

$$PF = f(PC, PG, PO) \qquad [II\text{-}4\text{-}8]$$

PF now represents the price of the energy aggregate, the equation [II-4-8] is the fuel submodel in which specific fuel inputs are determined.

A result of imposing separability is that the ratio of the cost shares of any two fossil fuels is independent of the prices outside the energy aggregate, which means that the ratio of the shares depends only on the fuel prices. Griffin argues that this may not be too unrealistic as costs for coal-fired plants seldom exceed the cost of a gas-fired plant by 25%. Thus with fairly similar capital costs, the BTUs of various fuels are "in principle, highly fungible".

Linear homogeneity in input prices implies that the cost share of fuels are independent of total expenditure on the energy group, so equations [II-4-7] and [II-4-8] can be estimated separately, so conserving degrees of freedom.

Griffin specifically excludes nuclear power as insignificant for his sample period, but adds: "were this study conducted 10 years later the significance of nuclear power would be sufficient to violate the separability conditions". MacAvoy (1969) shows that the choice between nuclear and fossil fuels depends inter alia on relative capital costs". Griffin also points out that: "While an energy aggregate is plausible in this case it seems highly implausible to hold in general. In most uses energy is not fungible and the existence of an energy aggregate is an empirical question". He cannot test for separability as he has no data on prices for capital and labour (although he quotes Berndt and Christensen (1973) as providing a good test were data available), nor can the full model be estimated.

Fuss (1977) does have the requisite data to run the full production or cost function model, which he does using an important approach which is also adopted by Fuss, Hyndman and Waverman (1977) and by Pindyck (1979).

Fuss' (1977) objective is to analyse the production structure in Canadian manufacturing within a model having 9 inputs: labour, capital, materials and six types of energy - "to incorporate numerous inputs into estimable production structures". The model assumes homothetic weak separability in the categories labour, capital, materials, energy. This reduces the estimation problem from:

(i) neoclassical production theory; 8 simultaneous equations with 42 unknown parameters,

to: (ii) a two-stage estimation process:-

(a) Stage One

Construct an energy sub-model (a valid procedure if the separability restriction is correct): "a firm will choose that mix of energy type which minimises the cost of the energy input, subject to those constraints imposed by the production technology on the ability to substitute one energy type for another".

Thus the production function is:

$$Q = f(E_1, \ldots, E_6, L, M, K) \qquad [II-4-9]$$

where

$E_1, \ldots, E_6$, are the six types of energy input

Assuming homothetic weak separability in energy means [II-4-9] may be written:

$$Q = f\{E(E_1, \ldots, E_6), L, M, K\} \qquad [II-4-10]$$

where

E is the homothetic aggregator function.

Duality theory shows the corresponding cost function to be weakly separable in the same partition:

$$C = C\{PE(PE_1, \quad ,PE_6), PL, PM, PK, Q\} \qquad [II-4-11]$$

where

PE is also an aggregator function, in this case the aggregate energy price index.

PE represents the price per unit of energy and is therefore the cost per unit to the manufacturer. This cost may be represented by an arbitrary unit cost function, and Fuss uses the translog. This is estimated under the restrictions implied by neoclassical production theory to give an estimate of the structure of substitution among energy types and the composition of energy components given any set of relative energy prices. Fuss then substitutes the parameter estimates into the original translog cost function to obtain an estimate $\hat{PE}$ of the aggregate price index to serve as an instrumental variable in the second stage of the estimation.

(b) Stage Two

Estimate the entire system subject to the constraints of neoclassical production theory, using the instrumental variable $\hat{PE}$ in place of PE. This now "allows for the possibility of both inter-fuel substitution and substitution among energy and non-energy factors of production". The econometric role of the assumption of homothetic weak separability lies in that it makes PE a function only of the energy prices PE_1 to PE_6, and not of PL, PM, PK and Q.

Fuss concludes that the empirical results for Canadian manufacturing provide support for the two-stage procedure ... "they imply the existence of a well-behaved neo-classical cost function representing a production structure with substitution possibilities that are reasonable a priori".

Pindyck (1979a) conducts a major study of sectoral energy demand, concentrating on residential, industrial and transportation demands. For the residential sector he uses the translog form to represent the indirect utility function. For the industrial sector he employs the translog cost function with the method exactly as in Fuss (1977). Fuss, Hyndman and Waverman (1977) use the translog form to analyse relative price effects in the forecasting of energy demand for the Canadian residential, commercial and industrial sectors to 1985. They also use the Fuss two-stage procedure, creating an aggregate price index $\hat{P}E$.

Moroney and Toevs (1978) focus on the increasing awareness of the significance of exhaustible resources for production costs. A process which uses such a resource as an "essential" input will face growing pressure as that resource becomes increasingly scarce. This leads Moroney and Toevs to an analysis of the possibilities for substitution between labour, capital and certain natural resource inputs, which they undertake for 7 "important resource-using industries of the US" 1954 - 1971. There are two major questions discussed. First Moroney and Toevs are interested in the extent to which it is possible to "substitute reproducible capital and labour either individually or jointly against natural resource inputs". Second whether there is "a general tendency for capital and resource inputs to be complementary". (Complementarity is defined here in two ways:

(i) a zero or negative Allen partial elasticity of substitution is defined as absolute complementarity

(ii) a positive Allen substitution elasticity lower than that between labour and natural resource inputs is relative complementarity). The translog functional form is adopted because it allows direct estimation of the elasticities of substitution of interest to Moroney and Toevs, without constraining, a priori, their values or constancy. Output is measured as the sum of constant dollar value added (deflated by the relevant industry wholesale price index), plus the constant dollar value of natural resource inputs. Defining net output in this way means that capital (K) labour (L) and natural resources (R) are assumed to be weakly separable from the remaining intermediate inputs (I):

$$V = f(K, L, R, I) \qquad [II\text{-}4\text{-}12]$$

$$= g\{h(K, L, R), I\} \qquad [II\text{-}4\text{-}13]$$

The function $h(K, L, R)$ now measures net output. One justification is that intermediate inputs in the industries under consideration are a minor part of total cost.

In 1980 Field and Grebenstein returned to the question of the substitution possibilities between energy and other inputs. They are concerned that various published studies do not reach the same conclusions, in particular for the relationship between capital and energy. The possibilities range from capital/energy complementarity, through no relationship, (where typically it is shown that various types of energy will serve as satisfactory substitutes for each other, but where substitutability between an aggregate "energy" and any other input is "limited"), to capital/energy substitutability. Studies concluding in favour of complementarity include Berndt and Wood (1975), Berndt and Jorgensen (1973), and Fuss (1977), while substitutability is found by Griffin and Gregory (1976), Pindyck (1979 a and b) and Halvorsen and Ford (1978).

As Pindyck (1979 a and b) points out, at any moment capital and energy are necessarily complementary because capital equipment is typically designed to operate using a given energy input. Rising energy prices would not, in the short term, lead to any large-scale substitution of other inputs; labour, possibly, although that would tend to be expensive, and capital improbably given the general inflexibility of manufacturing methods. However, Pindyck notes that this "may be far from true in the long-run".

The contrasting results are resolved by Field and Grebstein (F-G) (1980) by analysis of the two different approaches taken to defining the capital input. The first is the value-added approach in which:

$$\underset{\text{(CKV)}}{\text{cost of capital}} = \text{value added} - \text{payroll} \qquad \text{[II-4-14]}$$

The costs involved here include the costs of reproducible capital, of working capital, of land, inventories, indirect business taxes, economic rent, and will reflect any errors in the measurement of value added or of the wage bill.

The alternative is the service price approach where:

$$\underset{\substack{\text{capital} \\ \text{(CKS)}}}{\text{cost of reproducible}} = \underset{\text{capital}}{\text{quantity of physical}} \times \underset{\text{price}}{\text{service}} \qquad \text{[II-4-15]}$$

The difference between the two measures is defined by F-G to be the "cost contribution of working capital" (CKW):

$$\text{CKW} = \text{CKV} - \text{CKS} \qquad \text{[II-4-16]}$$

This quantity (CKW), will account for a large proportion of total capital cost which imples that studies taking the value added approach will be using a capital measure dominated by working capital. Should working capital and energy be substitutes, then the overall capital/energy relationship derived will show substitutability. Those studies using the far narrower (CKS) service price approach may be expected to find complementarity between physical capital and energy.

To test this F-G use a four input constant returns to scale cost function with two capital prices (physical capital and working capital), labour and energy. Material inputs should be included but there are no data, so F-G assume separability. The translog form is used, and the results show that reproducible capital and energy are generally complements while working capital and energy are generally substitutes. F-G conclude that on the aggregate level "a value added approach to capital cost would be expected to show capital/energy substitutability, while a service price approach to capital cost would show complementarity".

Berndt and Wood (1979) (B-W), are also concerned with the apparently opposing substitutability/complementarity conclusions on capital and energy. They themselves have demonstrated complementarity (1975) but they note engineering studies which show capital/energy substitutability. They also attempt to resolve these paradoxical conclusions.

Their analysis introduces the concept of "utilised capital", which refers to the output due to the combined inputs of capital and energy. Thus there is a "master" production function:

$$Q = f(K, L, E, M) \quad [II\text{-}4\text{-}17]$$

where

M is non-energy intermediate materials

From [II-4-17] is derived a two input separable subfunction with inputs capital and energy and output "utilised capital":

$$K^* = g(K, E) \quad [II\text{-}4\text{-}18]$$

There is also a second subfunction for L^* the output of labour and materials:

$$L^* = h(L, M) \quad [II\text{-}4\text{-}19]$$

The B-W argument is that engineering studies will typically focus on the subfunction [II-4-18] and, by virtue of dealing with only two inputs, will necessarily find substitutability. Essentially such studies are concerned with energy conservation for a given output and are dealing with the possibilities of moving along an isoquant for a given amount of utilised capital services - using less energy and more capital. However B-W demonstrate that energy and capital may still be shown to be complements. Suppose the price of capital falls, (B-W assume investment incentives). Within the framework of [II-4-18] above more capital will be substituted for less energy, and the price of K* falls. Reference to [II-4-17] shows that more K* is now substituted for less L*, meaning that the K* isoquant (from [II-4-18]) now shifts outward and more of both capital and energy are bought. If the overall effect is that more energy is used than previously, then econometric analysis will demonstrate that there is complementarity: factors which are substitutes in the subfunction are complements in the master function.

Uri (1982) estimates the demand for "motor gasoline, diesel fuel and aviation (jet) fuel" and electrical energy for transport. He then investigates the possibilities of inter-fuel substitution within the aggregate energy demand using a translog price possibility frontier, based on C-J-L (1971; 1973).

Uri (1981) also uses the translog price possibility frontier to undertake forecasting of demand for fuels in the USA and to analyse energy substitution in the Indian economy. In both cases aggregate energy inputs are taken to be a separable subset of the overall model. Hicks neutral technical change and constant returns to scale are assumed (justified by reference to Christensen and Greene (1976)). The results for the USA show comparatively smaller interfuel substitution effects than had been reported in the very limited number of similar studies for the U.S. The price elasticities of demand for fuels do show that changes in fuel prices have noticeable consequences for fossil fuel consumption. Similarly, the results of the analysis of energy substitution in the Indian economy show strong interfuel substitution with the commercial sector making relative price changes an important variable in the choice of energy input. In both cases Uri reports results implying that energy consumption does respond significantly to relative price changes amongst different fuels.

Williams and Laumas (1981) examine the substitution possibilities among energy inputs and other non-energy factors of production in response to price changes in India's manufacturing industries. In recent years Indian industries have been gradually moving towards a high energy-intensive structure of production. Factors other than labour tend to be fairly good substitutes for energy, and the own-price elasticity of energy is generally higher than the own-price elasticity of other inputs.

Hunt (1984) uses the translog model in an analysis of the substitutability or complementarity of capital, labour and energy in the U.K. industrial sector. His particular concern is with the relationship between capital and energy which his results show to be one of complementarity. The significance of this lies in government policy on energy prices. If these are kept "high", to encourage conservation or to generate revenue from the North Sea and the nationalised energy utilities, then the implication of the complementarity result is that capital investment will fall together with energy usage, and any given output level could only be maintained by substitution of more labour. Hunt finds capital and labour and energy and labour to be substitutes. Conversely, if government policy was aimed directly at increasing investment, then it should simultaneously increase the demand for energy and perhaps reduce that for labour.

Westoby and McGuire (1984) report a case study of the UK electricity industry, using a translog model to investigate input substitutability or complementarity. Their results show substitutability between capital and labour, and labour and energy; complementarity between capital and energy.

The general conclusion is that the translog model while not without its theoretical difficulties, does allow a methodologically satisfactory means of investigating factor substitutability, and has performed well in empirical work in the field of energy economics. Hence the decision to use it in the estimation reported in Chapter III is justified.

NOTES TO CHAPTER II

(1) Homogeneity and homotheticity in production functions

If a function is homogeneous of any degree then the slopes of the level curves (here the isoquants) are unchanged along any ray through the origin.

Consider the production function:

$$Q = f(X_1, \ldots, X_n) \qquad \text{(II-i)}$$

which is assumed homogeneous of degree r

The first partials of this function are homogeneous of degree r-1:

by assumption:

$$f(tX_1, \ldots, tX_n) = t^r f(X_1, \ldots, X_n)$$

now differentiate both sides with respect to X_i :

$$\partial f/\partial(tX_i) \,.\, \partial(tX_i)/\partial X_i = t^r \,.\, \partial f/\partial X_i$$

but

$$\partial f/\partial(tX_i) = t^{r-1} \,.\, \partial f/\partial X_i$$

that is, the function f_i evaluated at $(tX_1, \ldots, tX_n)$ equals $t^{r-1} f_i(X_1, \ldots, X_n)$. Thus f_i is homogeneous of degree r-1.

The slope of an isoquant from (II-i) in the X_iX_j plane is:

$$\partial X_j/\partial X_i = -f_i/f_j$$

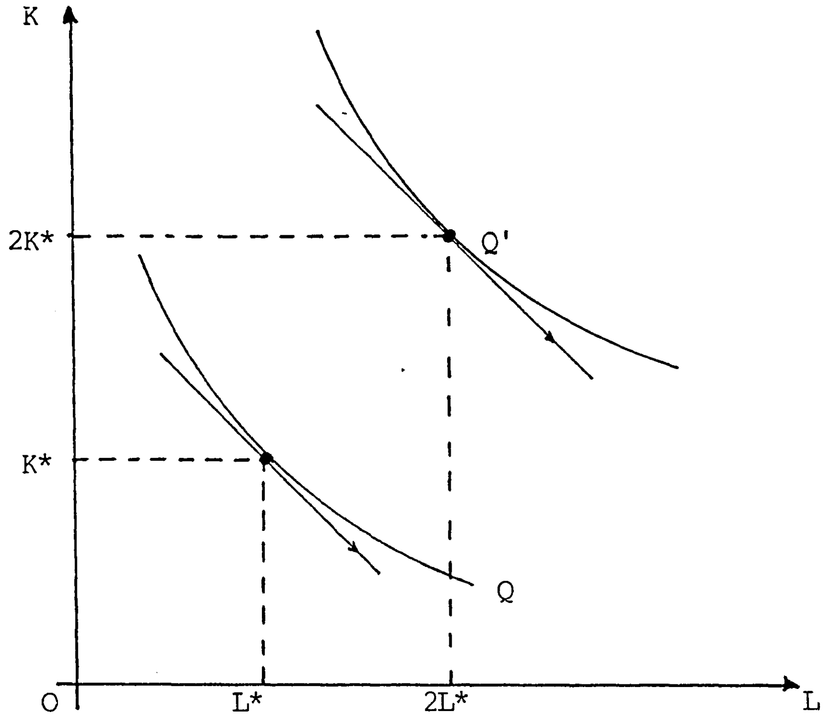
but

$$\frac{f_i(tX_1, \ldots, tX_n)}{f_j(tX_1, \ldots, tX_n)} = \frac{t^{r-1} f_i(X_1, \ldots, X_n)}{t^{r-1} f_j(X_1, \ldots, X_n)} = \frac{f_i(X_1, \ldots, X_n)}{f_j(X_1, \ldots, X_n)} \qquad \text{(II-ii)}$$

Thus the slope of any isoquant evaluated along a radial expansion of an initial point is identical to the slope at the original point.

Therefore the ratios of the marginal products along any ray from the origin remain unchanged for homogeneous functions, and the isoquants are radial blowups or reductions of each others.

Figure II-4 Homogeneous Production Function



Consider any point (L*,K*) on figure II-4. Double each input. If the production function is homogeneous of any degree, then the slope of the isoquant $-f_L/f_K$ will be the same at (2L*,2K*) as at (L*,K*). This is the economic interpretation of homotheticity.

A homothetic function is a monotonically increasing transformation of a homogeneous function. Any homogeneous function is homothetic, but homothetic functions are not necessarily homogeneous; for example, assume:

$$Q = f(X_1, \ldots, X_n) \qquad \text{(II-i)}$$

is homogeneous of degree r.

Let $Z = F(Q)$ (II-iii)

where

$F'(Q) > 0$

[F(Q) is a monotonic transformation of Q]

The function Z is a homothetic function.

Suppose the original function is

$$Q = L^{\alpha} K^{1-\alpha} \qquad \text{(II-iv)}$$

and the transformation F is "log", so that:

$$Z = F(L^{\alpha} K^{1-\alpha}) = \log(L^{\alpha} K^{1-\alpha})$$
$$= \alpha \log L + (1-\alpha) \log K \qquad \text{(II-v)}$$

Now, (II-iv) is homogeneous of degree 1, but (II-v) is not a homogeneous function:

$$f(tL, tK) = \alpha \log t.L + (1-\alpha) \log t.K$$
$$= \alpha(\log t + \log L) + (1-\alpha)(\log t + \log K)$$
$$= \log t + \log (L^{\alpha} K^{1-\alpha}) \neq t^{r} f(L, K)$$

However $\alpha \log L + 1-\alpha \log K$ is homothetic. The slope of an isoquant is

$$-fL/fK = -(\alpha /L)/(1-\alpha)/K$$
$$= \frac{-\alpha}{1-\alpha} \cdot \frac{K}{L}$$

That is, $-fL/fK$ is unaffected by changing K and L by a factor of t, thus the slopes of the isoquants are the same along any ray from the origin, which is the homotheticity property.

(2) There is a pricing agreement - the November 1983 Understanding - between the CEGB and NCB, holding coal price increases below the rate of inflation. The Understanding expires in 1987.

(3) Discussed in Chapter IV.

(4) Separability

Consider a production function:

$$Q = f(X_1, \ldots, X_n) \qquad \text{(II-i)}$$

There is a set of n inputs, denoted N = (1 ... n) which may be partitioned into r mutually exclusive and exhaustive subsets (N_1 ... N_r). This is known as the partition R.

The first and second partials of the production function are written:

$$f_i = \frac{\partial f}{\partial X_i} \qquad i = 1 \ldots n \qquad \text{all input levels other than } X_i \text{ held constant}$$

$$f_{ij} = \frac{\partial^2 f}{\partial X_i \, \partial X_j} \qquad i, j = 1 \ldots n \qquad \text{all input levels other than } X_i, X_j \text{ held constant}$$

The production function is homothetically weakly separable with respect to the partition R if the marginal rate of substitution between any two inputs X_i and X_j from any subset Nm (m = 1 ... r), is independent of output and the quantities of inputs outside of Nm:

$$\frac{\partial (f_i/f_j)}{\partial X_k} = 0 \qquad \text{for all i, j belonging to Nm and all k not belonging to Nm}$$

This may also be written:

$$f_j . f_{ik} - f_i . f_{jk} = 0 \qquad \text{(II-vi)}$$

$$\left[\quad \frac{\partial (f_i/f_j)}{\partial X_k} = \frac{\dfrac{\partial f}{\partial X_j} . \dfrac{\partial^2 f}{\partial X_i \, \partial X_k} - \dfrac{\partial f}{\partial X_i} . \dfrac{\partial^2 f}{\partial X_j \, \partial X_k}}{\dfrac{\partial f}{\partial X_j} . \dfrac{\partial f}{\partial X_j}} \right.$$

$$= \frac{f_j . f_{ik} - f_i . f_{jk}}{(f_j)^2}$$

$$\left. = 0 \qquad \text{if } f_j . f_{ik} - f_i . f_{jk} = 0 \quad \right]$$

The production function is strongly separable with respect to the partition R if the marginal rate of substitution between any two inputs from subsets Nm and Ns does not depend on the quantities of inputs outside Nm and Ns:

$$\frac{\partial(f_i/f_j)}{\partial X_k} = 0 \qquad \text{for } \begin{array}{l} i \text{ belonging to Nm} \\ j \text{ belonging to Ns} \\ k \text{ belonging to neither Nm nor Ns} \end{array}$$

[or:

$f_j . f_{ik} - f_i . f_{jk} = 0$]

Thus suppose the production function [II-37] had three capital inputs (K_1, K_2, K_3), three labour inputs (L_1, L_2, L_3), and three fuel inputs (C, O, U):

$$Q = f[K(K_1, K_2, K_3), L(L_1, L_2, L_3), F(C, O, U)] \qquad \text{(II-vii)}$$

The partition R: $r = 3$

Then

$$MRS(C, O) = (\partial f/\partial C)/(\partial F/\partial O)$$

and if

$$\frac{\partial MRS(C, O)}{\partial K_1} = 0$$

then the production function is weakly separable.

And if

$$\frac{\partial MRS(C, K_1)}{\partial L_1} = 0$$

then the production function is strongly separable.

Homothetic weak separability with respect to the partition R is a necessary and sufficient condition for the production function to be of the form:

$$F(X^1, X^2, \ldots X^r) \qquad \text{(II-viii)}$$

so that X^m is a strictly quasiconcave homothetic subfunction of only the elements within Nm :

$$X^m = fm(xi) \qquad \text{for all i belonging to Nm} \quad \text{for m = 1 ... r}$$

X^m is a consistent aggregate index of the inputs in Nm. The significance of this is that it means that there may only be a consistent aggregate index of a subset of inputs if that subset is weakly separable from all other inputs. That is, if the intention is to use a model involving a fuel input aggregate then it must be the case that the fuel components are homothetically weakly separable from all other non-fuel inputs if the procedure is to be valid.

CHAPTER III

ECONOMETRIC ESTIMATION AND RESULTS

Using the theory developed in Chapter II, this chapter presents the results of estimating the translog model with data series on the production of electricity by the CEGB. It is divided into two sections; the first deals with the data themselves, the second discusses the results of the estimation.

III.1 DATA

All data used in the estimation were taken from the following sources:

1. Handbook of Electricity Supply Statistics - published annually by the Electricity Council.
2. Digest of UK Energy Statistics - published annually for the Department of Energy by HMSO
3. a) Central Electricity Generating Board Statistical Yearbook
   b) Central Electricity Generating Board Annual Report and Accounts, both published by the CEGB.
4. National Institute Economic Review published quarterly by the National Institute of Economic and Social Research.
5. Price Index Numbers for Current Cost Accounting, Department of Industry 1981.
6. UK National Accounts 1985 Edition C.S.O.

Coal

Data on quantities and prices of coal burnt by the CEGB are to be found in each of references 1, 2 and 3 above.

Oil

Data on quantities and prices of oil burnt by the CEGB are to be found in each of references 1, 2 and 3 above. The data are given as both million tonnes of oil and million tonnes of coal equivalent. The former data were used, and the price of oil per tonne adjusted to account for the higher calorific value of a tonne of oil compared with a tonne of coal.

Nuclear Fuel

Quantity data for nuclear fuel are published in reference 1 (HESS 1984 table 20) both as tonnes of uranium and kilo tonnes of coal equivalent. The same source gives total works cost in pence per kWh of nuclear fuel in supplying electricity and the total output in gigawatt hours of nuclear power stations. These figures make it possible to construct a price series for nuclear fuel to use with the published price series for coal and oil.

Fuel Price Index

(i) An index was constructed from the estimates derived in the fuel subsystem (see the Results section).

(ii) An index was constructed using data published in reference 1 in the following manner:

$$\text{TOTAL COST OF FUEL} = \text{FOSSIL FUEL WORKS COST OF GENERATION} \times \text{FOSSIL FUEL STATIONS' OUTPUT} + \text{NUCLEAR FUEL WORKS COST OF GENERATION} \times \text{NUCLEAR FUEL STATIONS' OUTPUT}$$

$$\text{PRICE} = \text{TOTAL COST OF FUEL/FUEL USED IN MILLION TONNES OF COAL EQUIVALENT}$$

(iii) An index was constructed using the variable 'expenditure on fuel' generated in estimating the fuel subsystem and total fuel used in million tonnes of coal equivalent.

The choice of which of these three indices to use is discussed in the Results section. Their values are given in Table III.1

The significance of approach (i) (above) is it makes use of a (translog) aggregator function that does not require the index to be a weighted average of the individual fuel prices, which is essentially the case for approaches (ii) and (iii). However the correlation coefficients between the three indices (quoted in the Results section) show that little information is gained by using (i).

Table III.1

	Index Numbers for the Price of Fuel			
	a	b	c	d
1963/4	1.00	6.11	60.15	32.73
1964/5	1.04	6.22	62.22	33.22
1965/6	1.35	6.46	63.05	32.52
1966/7	1.02	6.13	68.96	36.86
1967/8	0.90	6.02	70.41	37.42
1968/9	0.93	6.05	69.63	37.49
1969/70	1.02	6.14	71.58	38.39
1970/1	0.61	5.27	83.51	44.89
1971/2	0.68	5.80	95.46	50.25
1972/3	0.69	5.80	100.00	51.27
1973/4	-0.02	5.08	117.51	59.54
1974/5	-0.84	4.27	186.39	100.00
1975/6	-1.36	3.75	241.70	131.15
1976/7	-1.93	3.18	276.29	153.61
1977/8	-2.07	3.04	314.03	175.42
1978/9	-2.30	2.81	338.07	193.10
1979/80	-3.02	2.09	412.66	223.69
1980/1	-3.43	1.68	499.81	280.78
1981/2	-4.11	1.00	553.15	328.73
1982/3	-4.11	1.00	576.92	338.56

a, b correspond to (i) above; a has 1963/4 as the base year, b has 1982/3 as the base year.

c corresponds to (ii) above.

d corresponds to (iii) above.

Hydroelectricity, pumped storage and gas were all ignored as either constant over the period or too small to be relevant in the estimation.

Output

Data on electricity output are available from each of references 1, 2 and 3.

Labour

Numbers employed are available from the CEGB Annual Report and Accounts, and from the Handbook of Electricity Supply Statistics. The price of labour was taken from the latter as average gross weekly earnings of full time manual men over 21. The tables also gives average hours worked, hence expenditure on labour may be calculated.

Capital

Three alternative measures of the price of capital were assembled.

(i) Following the approach in Desai (1976) the cost of capital was calculated as:

$$C = P(r + \delta) - \Delta P$$

where

P = capital goods price index (published in reference 5)

r = average flat yield on $2\frac{1}{2}$ per cent consols (published in Annual Abstract of Statistics)

δ = depreciation rate, taking an assumed value

(ii) Following the approach in Westoby and McGuire (1984) a price for capital was calculated by dividing "net expenditure on fixed assets plus initial fuel for nuclear power stations by declared gross capability of generating plant" (1). Both series are published in reference 1 above.

(iii) The National Institute of Economic and Social Research have published an index for the price of capital in the quarterly National Institute Economic Review.

The calculation in (i) yielded an index which was very unstable and entirely at odds with (ii) and (iii). The value of δ was assumed to be 5 percent which had the merit of preventing the calculated values of C from occasionally becoming negative (a particular problem given that the model requires taking the logarithm of the explanatory variables). Consequently only approaches (ii) and (iii) were retained and eventually (ii) was used (as discussed in the Results section).

The quantity of capital was taken to be total installed capacity, published in references 1 and 3a above.

Given the series referred to above, total expenditures, factor shares and prices may be derived either directly or by calculation. Normalisation of the data is accomplished by using indices. In the estimation of the fuel subsystem the nuclear fuel share is tiny in comparison to the coal and oil shares and the nuclear fuel price series is the result of a set of transformations of published data whereas coal and oil prices are listed directly. Similarly in the estimation of the overall cost function the fuel share is comparatively small.

The figures presented below represent the major features of the data.

Fig III-1 Fuels used by CEGB (mtce)

Fig III-2 Individual fuel shares in total expenditure

Fig III-3 Employees/GWh generated

Fig III-4 Index numbers of output capacity and employment

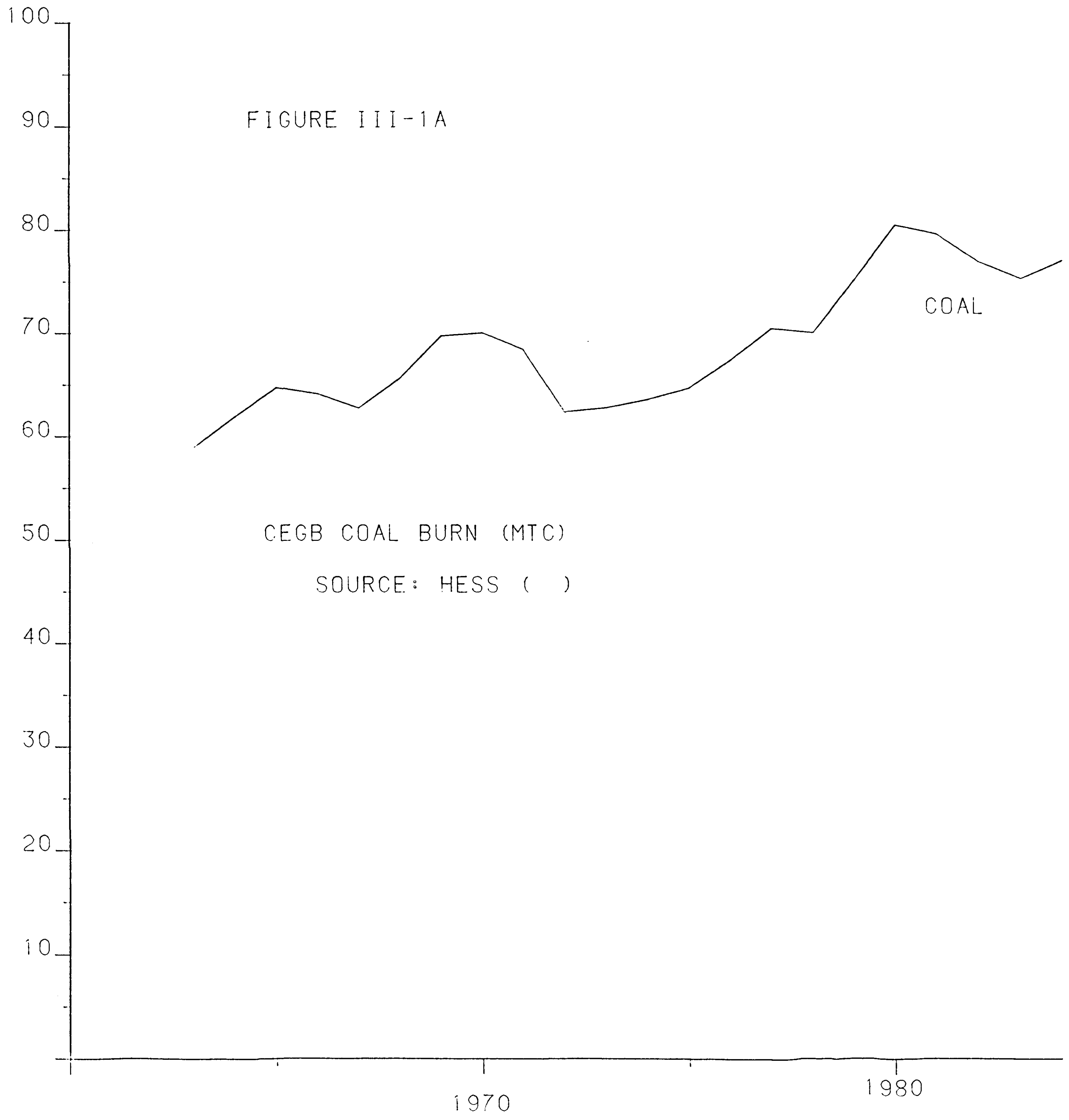


FIGURE III-1A

CEGB COAL BURN (MTC)

SOURCE: HESS ( )

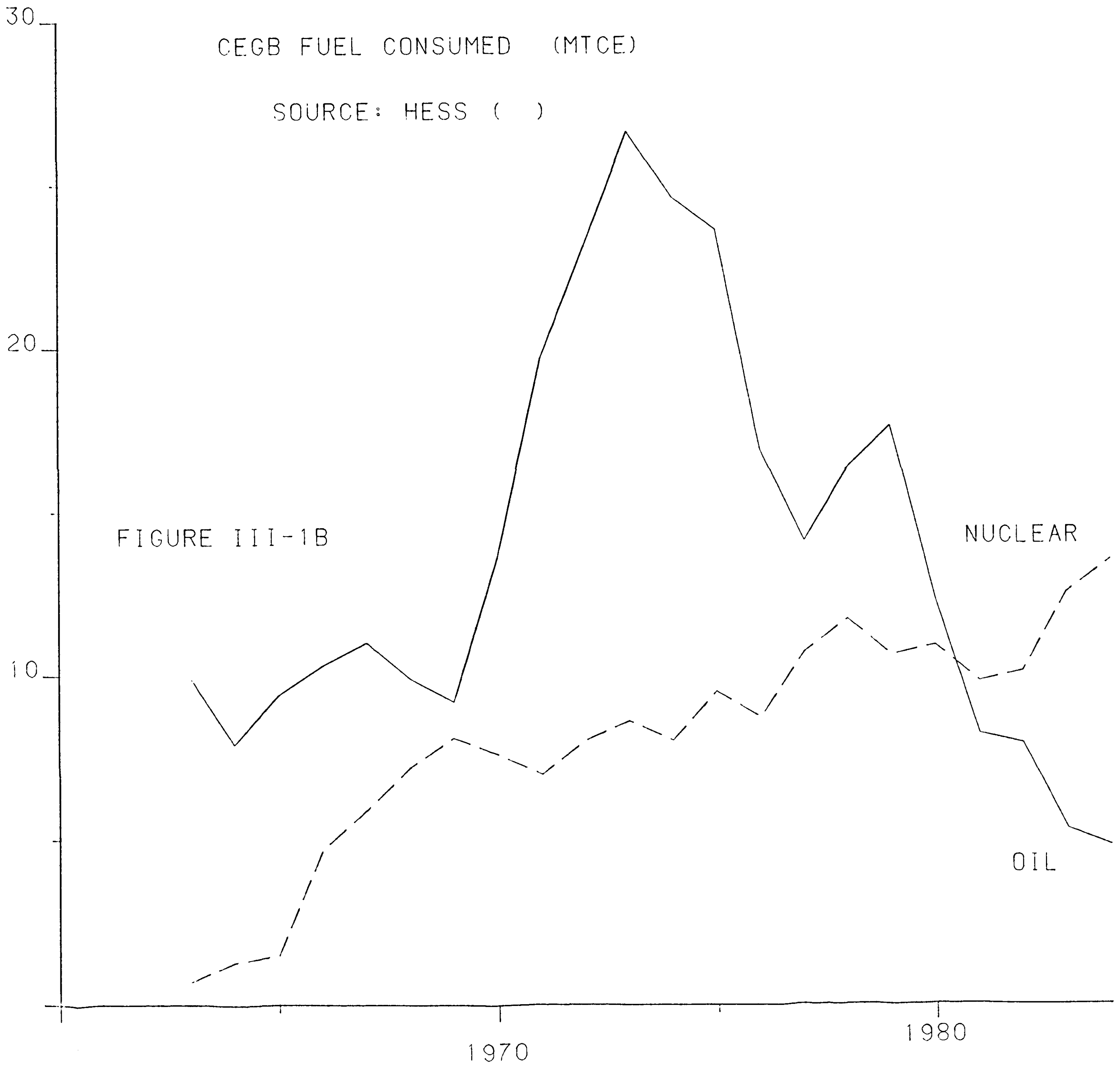


FIGURE III-1B

CEGB FUEL CONSUMED (MTCE)

SOURCE: HESS ( )

FIGURE III-2

CEGB INDIVIDUAL FUEL SHARES
IN TOTAL EXPENDITURE
SOURCE: HESS ( )

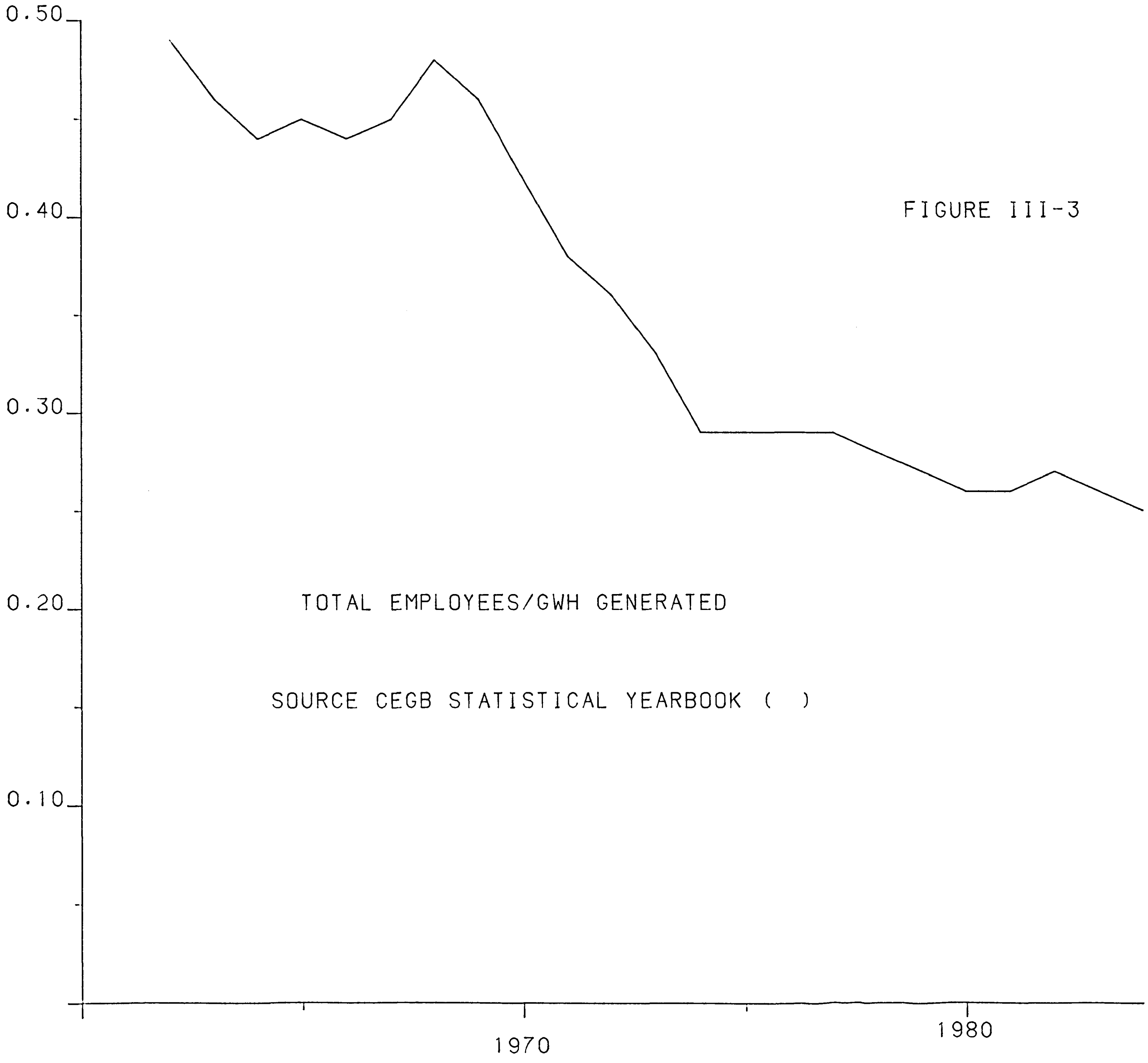


FIGURE III-3

TOTAL EMPLOYEES/GWH GENERATED

SOURCE CEGB STATISTICAL YEARBOOK (   )

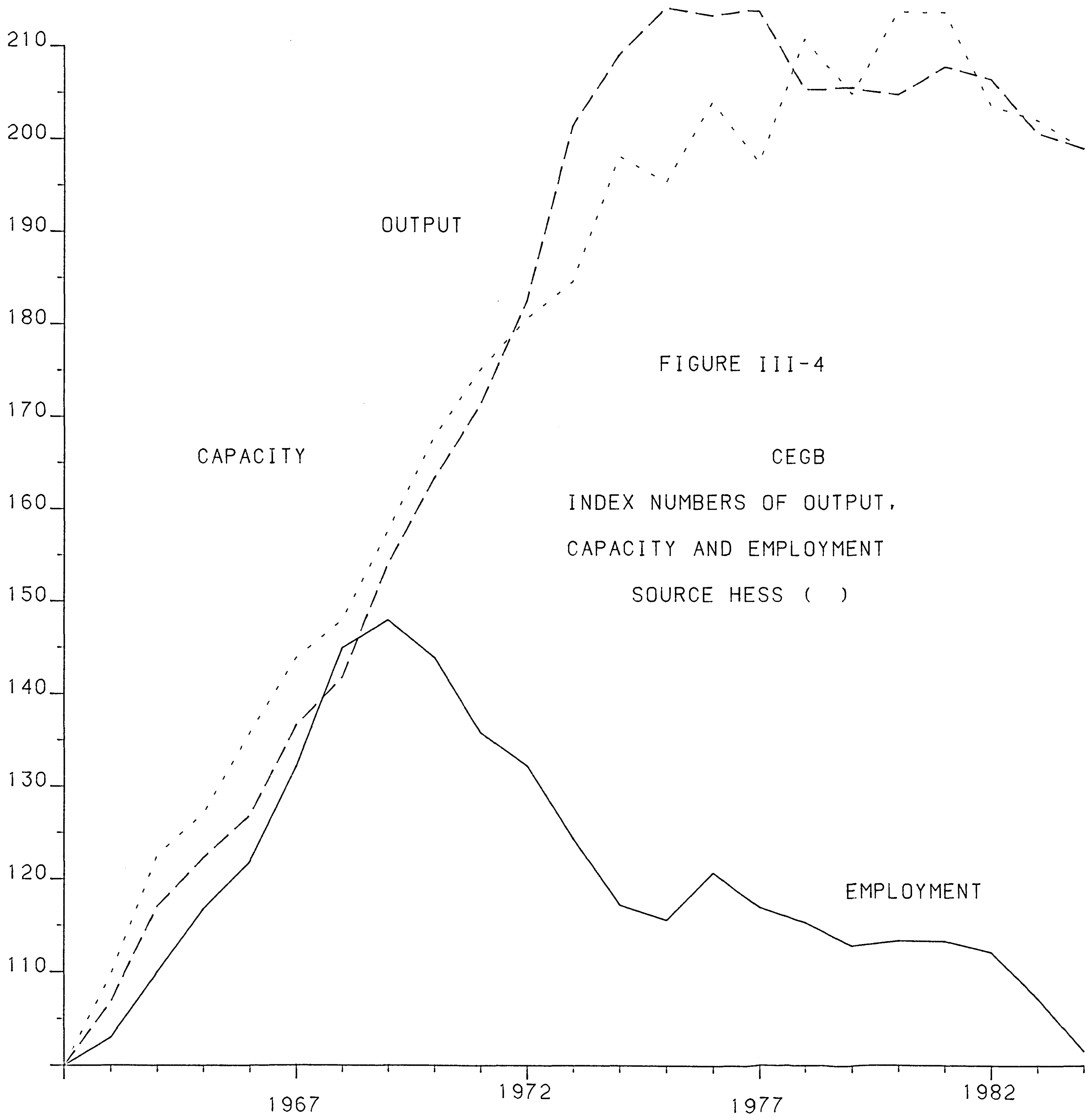


FIGURE III-4

CEGB

INDEX NUMBERS OF OUTPUT,
CAPACITY AND EMPLOYMENT

SOURCE HESS ( )

III.2 ESTIMATION OF THE MODEL

Following the procedure outlined in Chapter II, the estimation is undertaken first for the fuel subsystem, then for the overall model.

III.2.1 The Fuel Subsystem : Inter-fuel Substitution Possibilities

The initial share equations in the fuel subsystems are:

$$\begin{array}{l} \text{SHARE OF} \\ \text{COAL IN} \\ \text{TOTAL FUEL} \\ \text{EXPENDITURE} \\ \text{(COALSHARE)} \end{array} = \alpha_c + \beta_{cc} \log \begin{array}{c} \text{PRICE} \\ \text{OF COAL} \\ \text{(PC)} \end{array} + \beta_{co} \log \begin{array}{c} \text{PRICE} \\ \text{OF OIL} \\ \text{(PO)} \end{array} + \beta_{cn} \log \begin{array}{l} \text{PRICE OF} \\ \text{NUCLEAR} \\ \text{FUEL} \\ \text{(PNF)} \end{array} + e_c$$

$$\begin{array}{l} \text{SHARE OF} \\ \text{OIL IN} \\ \text{TOTAL FUEL} \\ \text{EXPENDITURE} \\ \text{(OILSHARE)} \end{array} = \alpha_o + \beta_{oc} \log \begin{array}{c} \text{PRICE} \\ \text{OF COAL} \\ \text{(PC)} \end{array} + \beta_{oo} \log \begin{array}{c} \text{PRICE} \\ \text{OF OIL} \\ \text{(PO)} \end{array} + \beta_{on} \log \begin{array}{l} \text{PRICE OF} \\ \text{NUCLEAR} \\ \text{FUEL} \\ \text{(PNF)} \end{array} + e_o$$

$$\begin{array}{l} \text{SHARE OF} \\ \text{NUCLEAR} \\ \text{FUEL IN} \\ \text{TOTAL FUEL} \\ \text{EXPENDITURE} \end{array} = \alpha_n + \beta_{nc} \log \begin{array}{c} \text{PRICE} \\ \text{OF COAL} \\ \text{(PC)} \end{array} + \beta_{no} \log \begin{array}{c} \text{PRICE} \\ \text{OF OIL} \\ \text{(PO)} \end{array} + \beta_{on} \log \begin{array}{l} \text{PRICE OF} \\ \text{NUCLEAR} \\ \text{FUEL} \\ \text{(PNF)} \end{array} + e_n$$

Of these the coalshare and oilshare equations were estimated and from those results, the coefficients in the nuclear fuel share equation may be inferred at each stage, as restrictions are imposed and the equations re-estimated. Following Maddala (1979), the estimation method is ordinary least squares, which in these circumstances is the maximum likelihood technique.

Prior to estimation of the share equations, it is clear that the price series for coal and oil, at least, are likely to be highly correlated. The rapid escalation of the price of oil since 1973/4 has, arguably, been the means used by the National Coal Board to push up the price of coal. Whatever its cause, the closeness of the relationship is shown by regressing the price of coal on the price of oil:

PRICE OF COAL	=	160.7	+	0.357	PRICE OF OIL
Standard error		42.5		0.0088	
t statistic		3.78		40.75	

$\overline{R}^2 = 0.989$ $F_{(1,\ 18)}$ 1660.2 DW = 1.823

The above result shows clearly that the two prices are strongly linked, the coefficient on the price of oil being very significant, the R statistic being close to one, the $F_{1\ 18}$ statistic being very large. Since the price of oil is internationally determined it seems reasonable to estimate the equation in the form above.

The series on the price of nuclear fuel was constructed by manipulation of various published series (see the 'Data' section). The uranium market is international, but the processing (discussed in Chapter V) is not subject to similar competitive forces and does not, in general, publish cost and price data. Given the result above between coal and oil prices, the derived series on price of nuclear fuel was regressed on the price of oil:

PRICE OF NUCLEAR FUEL	=	-143.1	+	0.393	PRICE OF OIL
Standard error		93.64		0.019	
t statistic		1.53		20.3	

$\overline{R}^2 = 0.956$ $F_{(1\ \ 18)} = 413.95$ DW = 1.38

Whereas an argument giving a casual relationship between coal and oil prices may be made, it is not the intention of this brief section to do so; nor is any similar argument and oil and nuclear fuel prices to be developed here. The relevant point is that these simple regressions show that there is a highly significant relationship between the prices; since the latter are the regressors in the share equations then, a priori, estimation problems may be anticipated. Multicollinearity is probable and the standard test statistics are therefore to be expected to show that the estimated equations fit the data inadequately.

An additional problem relates to the structure of the data. Throughout the sample period the fuel shares (both in terms of quantity - million tonnes of coal equivalent - and expenditure), are heavily dominated by coal. The nuclear component is particularly tiny, reaching 10% of the total only in 1979/80 - the seventeenth year of the twenty observations. Conversely the coalshare falls below 70% on only six occasions and is 80% or above on seven. This substantial imbalance could also cause the estimates to fit badly.

The results of estimating the initial share equations are:

SHARE OF COAL	= 1.23 -	0.18 log PC -	0.17 log PO +	0.3 log PNF
Standard error	0.24	0.20	0.13	0.096
t statistic	5.17	-0.87	-1.26	3.1

$\bar{R}^2 = 0.36$ $F_{3\ 16} = 4.63$ DW = 1.14 SSR 0.057

SHARE OF OIL	= -0.08 +	0.13 log PC +	0.198 log PO -	0.31 log PNF
Standard error	0.23	0.202	0.13	0.094
t statistic	-0.33	0.62	1.52	-3.2

$\bar{R}^2 = 0.39$ $F_{3\ 16} = 4.98$ DW = 1.011 SSR 0.056

These results confirm the expectation that the estimation would encounter difficulties due, at least in part, to the collinearity of the regressors. The F statistics are both very low and barely satisfy the test for the overall significance of each regression:

$$F^{0.05}_{3\ 16} = 3.24$$

$$F^{0.01}_{3\ 16} = 5.29$$

The computed F statistics are 4.63 and 4.98 and so each is greater than the tabulated value at the 5% level of significance (but below that at the 1% level).

The Durbin Watson statistics both fall in the inconclusive range:

20 observations, 3 explanatory variables $d_L = 1.00$, $d_u = 1.68$;
Coalshare DW = 1.14; Oilshare DW = 1.011

The adjusted R^2 statistics are extremely low, and of the eight coefficients estimated only three are statistically significant: the constant in the coalshare equation and the log of the price of nuclear fuel in both equations. Assuming adjustment in the input mix is rapid, an increase in the price of any fuel should, a priori, cause it to be used less and so reduce the share of that fuel in total expenditure. Thus, although not significant, the coefficient on coal price in the coalshare equation is negative as the above argument predicts; however so is the coefficient on oil price. In the oilshare equation the oil price coefficient is positive but the nuclear fuel price coefficient is negative. However the fact that the coefficients' signs appear not to satisfy the argument is not necessarily important. What would cause the input mix to alter would be changes in relative prices, which these equations do not show;

second, adjustment may well be a fairly lengthy process which is not satisfactorily mirrored in equations with no dynamics or lagged adjustment process. It will be argued later that the structure of production chosen by the CEGB is such that the a priori argument on expected signs for the coefficients on fuel prices would be met only in cases of dramatic price change as in 1973/4. The graphs of fuel used by the CEGB (Fig. III-1) and of the fuel expenditures (Fig. III-2) show clearly the immediate reaction in that instance.

The next stage in the estimation procedure is to impose linear homogeneity which is provided for by the constraints:

$$\beta_{cc} + \beta_{co} + \beta_{cn} = 0$$

$$\text{and } \beta_{co} + \beta_{oo} + \beta_{on} = 0$$

or in general $\Sigma\beta_{ij} = 0 \quad i, j, = C, O, N$

The results are:

$$\text{COALSHARE} = 0.88 + 0.96 \log\left[\frac{\text{PCOAL}}{\text{PNF}}\right] - 0.3 \log\left[\frac{\text{POIL}}{\text{PNF}}\right]$$

Standard error	0.044	0.086	0.099
t statistic	20.1	1.11	3.07

$\bar{R}^2 = 0.32$ $\quad F_{2\ 17} = 5.498 \quad$ DW $= 0.75 \quad$ SSR 0.065

$$\text{OILSHARE} = 0.045 + 0.027 \log\left[\frac{\text{PCOAL}}{\text{PNF}}\right] - 0.25 \log\left[\frac{\text{POIL}}{\text{PNF}}\right]$$

Standard error	0.041	0.081	0.092
t statistic	1.11	0.33	2.7

$\bar{R}^2 = 0.41$ $\quad F_{2\ 17} = 7.7 \quad$ DW $= 0.87 \quad$ SSR 0.057

The estimation of this second stage also produces very poor results. Testing the overall significance of the regression shows the computed F statistics of 5.5 and 7.7 to be greater than the tabular value at the 5% significance level (3.59) but at the 1% level the tabular value is 6.11 which exceeds the computed coalshare statistic.

The computed Durbin Watson statistics are both now clearly in the region denoting positive autocorrelation:

20 observations, 2 explanatory variables $d_L = 1.10$ $d_u = 1.54$

coalshare DW = 0.75; oilshare DW = 0.87

The adjusted R^2 statistics remain very low and of the six estimated coefficients, three are significant: the constant in the coalshare equation and the coefficients on the variable $\log \left[\frac{POIL}{PNF} \right]$ in both equations.

If the quality of these results is temporarily ignored, the linear homogeneity restrictions may be tested. Here the null hypothesis is that the restrictions are true, the alternative hypothesis that not all the restrictions are true; (in this case one restriction on each equation). testing this requires computing the F statistic:

$$F^* = \frac{(SSR_R - SSR_u)/r}{(SSR_u)/n-k}$$

where SSR_R = sum of squared residuals in the restricted regression

SSR_u = sum of squared residuals in the unrestricted regressions

r = number of restrictions

$n-k$ = degrees of freedom in unrestricted regressions

Hence

$$F^* = \frac{(0.122 - 0.113)/2}{(0.113)/32} = 1.275$$

The tabular values are:

$$F^{0.05}_{2\ 32} \cong 3.32 \qquad F^{0.01}_{2\ 32} \cong 5.39$$

Since $F^* < F$ the null hypothesis cannot be rejected, hence the restrictions are accepted. However the results of this stage are so poor that the fact that the restrictions are passed is of little consequence.

It has been argued above that a major problem is the collinearity of the regressors; since the prices of the fuels are also likely to be moving together with a similar time trend, a possible solution to the poor results could lie in some transformation of the data aimed at eliminating both the common time trend and the high correlations between the explanatory variables. Accordingly, the equations were re-estimated with the variables transformed in the following ways:

(1) log of absolute value of first difference

$$\text{eg Log} \mid PC - PC_{-1} \mid$$

(since the fuel prices both rose and fell, the first differences were occasionally negative for each of them; as it would not have been possible to take the logarithm as required by the model, the absolute value was used).

(2) log of square of first differences

$$\text{eg log} \left[(PC - PC_{-1})^2 \right]$$

(for the same reason as (1) - this is obviously almost the same model).

(3) first difference of logs

eg $\log PC - \log PC_{-1}$

(approximately the rate of change of each price)

(4) original equations estimated using the Cochrane-Orcutt procedure.

(5) log of absolute value of first differences, using the Cochrane-Orcutt procedure.

In each case the results deteriorated substantially, and in general they are too poor to quote. This may have been expected in that there is already a small sample size and the transformations reduce it; and the relationship between fuel share and the first difference in fuel price may involve dynamics not accounted for in the equation.

III.2.2 Use of a Dummy Variable

An alternative means of improving the results lies in noting that the world fuel market has suffered violent and abrupt shocks since the 1970s. Fuel prices have become much more volatile since that period, reacting not merely to the direct interventions of OPEC, but also to market expectation of such intervention and to associated political events. The implication is that the CEGB would attempt to adjust its fuel input mix not simply according to prices as they are altered in the market; it would also adjust in the light of its own expectation of the future trend of prices given its current information. This is approximately a "rational expectations" argument, and is intended to make the point that, since the early 1970s, any energy based firm has, of necessity, been required to form expectations of price trends and act accordingly; until a comparatively recent downturn in the real oil price, failure to act in this fashion would have proved extremely costly. Hence, a dummy variable may be constructed to pick up the most notable events which may have been expected to influence the CEGB in its decision on fuel input mix. The years chosen to take the value one in the dummy variable are 1970/1; 1972/3; 1973/4; 1974/5; 1978/9; 1979/80; 1981/2.

1970/1 was chosen to reflect both domestic and international events. In December 1970 there was a work to rule and overtime ban by workers in the electricity supply industry in dispute over a pay offer. A Court of Inquiry under Lord Wilberforce resulted in a pay rise well above the Electricity Council's final offer. Coal prices were raised 10% in January 1970 and the industrial coal prices a further 16% in November 1970. In addition in that year Iran made moves to increase the price of its crude oil, and increased oil prices became the policy of the major oil exporters.

In January 1972 members of the NUM voted for a strike which finally ended on 25 January 1972. The dispute with the government involved the imposition of fuel rationing limitation on "extraneous" use of electricity (for advertising, shop signs and so on) and a three day week for industry. This is viewed as being significant for the year 1972/3 and together with further OPEC pressure for price rises for crude oil justifies the inclusion of that year.

The period 1973/4 to 1974/5 has obvious reasons for being included. The Middle East war broke out on 6 October 1973. On 16 October the Arab oil producers raised the posted price of oil by 66%; on 17 October they announced a 5% per month cumulative cut back in oil production and in early November began to cut supplies to the West. Prior to Christmas 1973 the posted price of oil was doubled, to take effect from January 1 1974 (although the output cutbacks were also eased). Throughout 1974 the price of crude was raised further by the newly powerful OPEC.

In November 1973 both the Electrical Power Engineers Association (1 November) and the NUM (12 November) began industrial action over pay claims disallowed by the current incomes policy. On November 13 the government announced a state of emergency, with power rationing followed by rationing of petroleum products and restrictions on street and office lighting. A three day week for industry was introduced on 1 January 1974 and the miners went on strike on 10 February 1974.

The Iranian revolution happened in 1978 causing a dramatic disruption to the West's oil supplies and further upward pressure on oil prices. OPEC Ministers were meeting throughout the 1978/9 - 1979/80 period and there was a continual series of individual countries raising crude prices. For example in October 1979 both Kuwait and Iraq raised oil prices; in December 1979 Saudi Arabia, Libya and Kuwait did so and an OPEC meeting on oil pricing failed to reach agreement. Also in November and December of 1979 the manual workers at British Nuclear Fuels gained a pay rise of between 23% and 27% and the miners one of 20%. Throughout January and February Saudi Arabia, Kuwait, Iraq, UAE, Qatar, Algeria, Indonesia, BNOC, Iran, Nigeria all raised their crude oil prices and on 14 February the National Coal Board increased the price of coal to industry by 20%.

OPEC Ministers announced agreement on a long term pricing system for crude oil on May 8 1980. However 1981/2 is included in the dummy variable as the beginning of the price fall for oil. In April 1981 Saudi Arabia cut its oil price to countries affected by the Iran-Iraq war; and then cut production in August and October. BNOC, Nigeria, Iran and Mexico all cut prices in the period June 1981 to March 1982 and the October 1981 OPEC meeting which agreed to reunify prices and then freeze the agreement for a year was overturned by OPEC price cuts in December 1981 and OPEC output reductions agreed on 7 March and 21 March 1982 (to attempt to halt the price slide). Finally on 2 April 1981 manual workers in the electricity supply industry were awarded a pay increase of 13% (2).

Thus, seven years were taken as exceptional and represented by a value of one in the dummy variable, the remaining thirteen years taking the value zero. Reestimation of the initial share equations yielded:

COALSHARE	= 1.26	- 0.09D	- 0.27 log PC	- 0.11 log PO	+ 0.32 log PNF
Standard error	0.16	0.02	0.14	0.09	0.064
t statistic	8.02	-4.6	-1.93	-1.2	4.99

$\bar{R}^2 = 0.72$ DW = 1.95 $F_{4\ 15} = 13.2$ SSR 0.024

OILSHARE	= -0.11	+ 0.086D	+ 0.31 log PC	+ 0.14 log PO	- 0.33 log PNF
Standard error	0.16	0.02	0.14	0.09	0.065
t statistic	-0.7	4.32	1.48	1.52	-5.01

$\bar{R}^2 = 0.71$ DW = 1.68 $F_{4\ 15} = 12.52$ SSR 0.0249

The inclusion of the dummy variable has improved the results substantially. The adjusted R^2 statistics have nearly doubled and the F statistics have more than done so. The tabular F values, testing the significance of the regression as a whole are: $F^{0.05}_{4\ 15} = 3.06$; $F^{0.01}_{4\ 15} = 4.89$, and the computed values are now satisfactorily above both of these. The Durbin Watson statistics show no autocorrelation in the coalshare equation and an inconclusive result in the oilshare equation:

20 observations, 4 explanatory variables, $d_L = 0.9$ $d_u = 1.83$;
Coalshare DW = 1.95; oilshare DW = 1.68

The dummy variable in each equation is statistically significant and of the other eight coefficients estimated three are significant. These are the same coefficients that were significant in the initial estimation, however the t statistics generally show a marked improvement when the dummy variable is included.

Linear homogeneity is now imposed by the constraint:
$\sum\beta_{ij} = 0$ (i, j = C O N) and the reestimated results are:

$$\text{COALSHARE} = 0.91 - 0.09D + 0.022 \log\left[\frac{\text{PCOAL}}{\text{PNF}}\right] - 0.25 \log\left[\frac{\text{POIL}}{\text{PNF}}\right]$$

Standard error	0.032	0.022	0.065	0.073
t statistic	28.1	-4.1	0.34	-3.4

$\bar{R}^2 = 0.64$ DW = 1.36 $F_{3\ 16} = 12.5$ SSR = 0.0321

$$\text{OILSHARE} = 0.023 + 0.086D + 0.098 \log\left[\frac{\text{PCOAL}}{\text{PNF}}\right] + 0.193 \log\left[\frac{\text{POIL}}{\text{PNF}}\right]$$

Standard error	0.03	0.02	0.059	0.066
t statistic	0.78	4.34	1.67	2.94

$\bar{R}^2 = 0.71$ DW = 1.51 $F_{3\ 16} = 16.72$ SSR 0.0261

Once again the inclusion of the dummy variable leads to a large improvement in the results, the changes being similar to those noted above. The adjusted R^2 statistics both rise, that on the coalshare equation to double its previous value, that on the oilshare by nearly 75%. The computed F statistics are 12.5 and 16.72 and compare favourably with the tabular values of $F^{0.05}_{3\ 16} = 3.24$, $F^{0.01}_{3\ 16} = 5.29$, which was not the case in the first estimation. An improvement is also shown in the Durbin Watson statistics:

20 observations, 3 explanatory variables $d_L = 1.00$ $d_u = 1.68$
Coalshare DW = 1.36; Oilshare DW = 1.51

The restriction of linear homogeneity may be tested (as above):

$$F^* = \frac{(SSR_R - SSR_u)/r}{(SSR_u)/n-k}$$

$$= \frac{(0.0582 - 0.0489)/2}{(0.0489)/30}$$

$$= 2.852$$

The tabular value $F^{0.05}_{2\ 30} = 3.32$

Since $F^* < F$ the null hypothesis that the restrictions are true may be accepted.

[However, if the F tests are undertaken separately for each equation, the restrictions are accepted only for the oilshare equation:

	SSR	
	unrestricted	restricted
coalshare	0.024	0.0321
oilshare	0.0249	0.0261

$$F^*_{\text{coalshare}} = \frac{(0.0321 - 0.024)}{(0.024)/15}$$

$$= 5.063$$

$$F^*_{\text{oilshare}} = \frac{(0.0261 - 0.0249)}{(0.0249)/15}$$

$$= 0.723$$

$$F^{0.05}_{1\ 15} = 4.54$$

Hence the coalshare equation fails marginally the test on the restrictions. Since a system is being analysed this may be ignored.]

The final stage in the estimation of this model is to impose the restriction of symmetry; in the case of the equation being estimated here, this implies the constraint: $\beta_{CO} = \beta_{OC}$. The two equations are stacked and estimated as one to accomplish this, (first without then with the dummy variable) in the form:

$$\begin{bmatrix} \text{COALSHARE} \\ \\ \text{OILSHARE} \end{bmatrix} = \alpha_C \begin{bmatrix} 1 \\ \\ 0 \end{bmatrix} + \alpha_O \begin{bmatrix} 0 \\ \\ 1 \end{bmatrix} + \alpha_{CD} \begin{bmatrix} D \\ \\ 0 \end{bmatrix}$$

$$+ \alpha_{OD} \begin{bmatrix} 0 \\ \\ D \end{bmatrix} + \beta_{CC} \begin{bmatrix} \log \frac{\text{PCOAL}}{\text{PNF}} \\ \\ 0 \end{bmatrix} + \beta_{OO} \begin{bmatrix} 0 \\ \\ \log \frac{\text{POIL}}{\text{PNF}} \end{bmatrix}$$

$$+ \beta_{OC} \begin{bmatrix} \log \frac{\text{POIL}}{\text{PNF}} \\ \log \frac{\text{PCOAL}}{\text{PNF}} \end{bmatrix}$$

The results obtained are: (i) without the dummy variable:

COALSHARE	$= 0.82$	$- 0.011 \log\left[\frac{PCOAL}{PNF}\right]$	$- 0.12 \log\left[\frac{POIL}{PNF}\right]$
Standard error	0.036	0.078	0.068
t statistic	22.74	-0.14	-1.73

OILSHARE	$= 0.03$	$- 0.12 \log\left[\frac{PCOAL}{PNF}\right]$	$+ 0.36 \log\left[\frac{POIL}{PNF}\right]$
Standard error	0.046	0.068	0.093
t statistic	0.64	-1.73	3.85

$\bar{R}^2 = 0.951$ DW $= 0.574$ $F_{4\ 35} = 189.7$ SSR 0.146

Although the previous regressions without the dummy variable have been rejected as inferior it is noticeable that the Durbin Watson statistic has altered to show positive autocorrelation:

40 observations, 3 explanatory variables $d_L = 1.34$ $d_u = 1.66$

Computed DW $= 0.574$

The test of the acceptability of the symmetry restriction fails:

$$F^* = \frac{(0.146 - 0.122)}{(0.122)/34}$$

$$= 6.7$$

$F^{0.05}_{1\ 34} \cong 4.17$, hence $F^* > F$ and the null hypothesis that the restrictions are true is rejected.

(ii) results with the dummy variable:

$$\text{COALSHARE} = 0.822 - 0.103D - 0.13 \log \left[\frac{\text{PCOAL}}{\text{PNF}} \right] + 0.0032 \log \left[\frac{\text{POIL}}{\text{PNF}} \right]$$

Standard error	0.023	0.024	0.054	0.0046
t statistic	35.1	-4.24	-2.42	0.7

$$\text{OILSHARE} = 0.018 + 0.075D + 0.0032 \log \left[\frac{\text{PCOAL}}{\text{PNF}} \right] + 0.27 \log \left[\frac{\text{POIL}}{\text{PNF}} \right]$$

Standard error	0.036	0.024	0.046	0.06
t statistic	0.5	3.11	0.7	4.41

$\bar{R}^2 = 0.97$ DW $= 1.08$ $F_{6\ 33} = 210.5$ SSR 0.0841

The adjusted R^2 and F statistics are both satisfactory but the Durbin Watson statistic shows evidence of positive autocorrelation:

40 observations, 5 explanatory variables $d_L = 1.23$, $d_u = 1.79$
Computed DW $= 1.08$

The symmetry restriction is tested and rejected:

$$F^* = \frac{(0.0841 - 0.0582)}{(0.0582)/32}$$

$$= 14.23$$

Since the tabular F value is $F^{0.05}_{1\ 32} \cong 4.17$, $F^* > F$ and the null hypothesis that the restriction (of symmetry) is true cannot be accepted.

Given the evidence of positive autocorrelation in the final stage of the analysis of the model, the stacked equation was reestimated using the Cochrane-Orcutt procedure as a means of dealing with first-order serial correlation. The results are shown in Appendix III.1. The Durbin Watson statistic improves in each case (moving to the inconclusive region for the equation without the dummy and just into the no autocorrelation region with the dummy), but the Cochrane-Orcutt procedure biases this statistic towards two and, as a result, the improvement is not remarkable. There is nothing else in the equation to render them preferable to those quoted above.

Since the symmetry restriction has been rejected, and the t statistics on three of the eight coefficients estimated (in the final regression, with the dummy variable) show them not to be statistically significant, it may be argued that these results should not be used. There are, however, alternative, stronger arguments in favour of retaining them. First, some research work using this model imposes the restrictions, a priori (and ignores the testing procedure undertaken here) - this is the case in, for example, Uri (1981), Westoby and McGuire (1984), Hunt (1984). Second, the structure of the data was argued, prior to the estimation, to be a probable cause of difficulty with the model. It may be the case that some degree of misspecification is causing the symmetry restriction to be rejected. The analysis of the theoretical model (above, Chapter II) showed that the symmetry restriction arises from the derivative of the relevant coefficients by partial differentiation of the cost. As the order of the double differentiation is irrelevant the theoretical result is that $\beta_{CO} = \beta_{OC}$ and so on. The data reject this, but imposing the restriction gives more significant coefficients, and, in the coalshare equation, the signs on the coefficients which would be expected, a priori. A final reason for accepting the last stage results is that the model itself may not be at fault. An underlying assumption of the model is that it is dealing with a cost minimising industry which will substitute inputs to that end. The CEGB does not switch fuels at will; nuclear power stations are run on base load and (with the exception of the 1984/5 miners' strike, not included in these observations), oil fired stations have been severely limited since the mid 1970s. There is also a fairly high level of excess capacity (28% in 1980). Thus cost minimisation may be applied by the CEGB in a manner which this fuel substitution model is not entirely suited to capturing : the station deemed "cheapest" by the CEGB (particularly nuclear but also some coalfired stations) run all the time, and the merit order brings other stations, and, therefore, a different fuel mix on and off stream as the load rises and falls. Any other substitution - for example constructing substantially more nuclear plant - is a very long term procedure, not picked up by the equation as it stands given its lack of dynamics and the small sample period. Hence, the coefficients estimated in the equation using the dummy variable and restricted to linear homogeneity and symmetry are used to derive the remaining coefficients; the elasticities of substitution and own- and cross-price elasticities; and the fuel price index to use as an instrumental variable in the next stage.

[The full set of coefficients is given in Appendix III.2].

The remaining coefficients may be inferred given the restriction of linear homogeneity ($\sum \beta_{ij} = 0$) and symmetry ($\beta_{ij} = \beta_{ji}$) from those estimated and reported above.

The three equations are stated at the beginning of this section. The adding up criterion (the shares sum to unity) implies that $\sum\alpha_i = 1$.

Thus:

$$
\begin{array}{llllll}
\text{(i)} & \alpha_c & + \alpha_o & + \alpha_n & = & 1 \\
\text{and} & 0.822 & + 0.018 & + \alpha_n & = & 1 \\
 & & & \alpha_n & = & 0.16
\end{array}
$$

$$
\begin{array}{llllll}
\text{(ii)} & \beta_{cc} & + \beta_{co} & + \beta_{cn} & = & 0 \\
 & -0.13 & + 0.0032 & + \beta_{cn} & = & 0 \\
 & & & \beta_{cn} & = & 0.1248
\end{array}
$$

$$
\begin{array}{llll}
\beta_{cc} & & = & -0.13 \\
\beta_{co} & = \beta_{oc} & = & 0.0032 \\
\beta_{cn} & = \beta_{nc} & = & 0.1248 \\
\beta_{oo} & & = & 0.27 \\
\beta_{on} & = \beta_{no} & = & -0.2732 \\
\beta_{nn} & & = & 0.1484
\end{array}
$$

Following the theoretical model discussed above, the coefficients are used together with the fuel shares to calculate the Allen partial elasticities of substitution and the own- and cross-price elasticities of demand. Writing the Allen partial elasticity of substitution between two inputs as A_{ij} Uzawa (1962) shows the calculation to be:

$$A_{ij} = \frac{\beta_{ij} + S_i S_j}{S_i S_j}$$

where

β_{ij} is the coefficient

S_i is the share of factor i

Also

$$A_{ii} = \frac{\beta_{ii} + (S_i^2 - S_i)}{S_i^2}$$

Once the Allen partial elasticities of substitution are calculated, the own- and cross-price elasticities (written E_{ii} and E_{ij}) may also be calculated:

$$E_{ij} = S_j \cdot A_{ij}$$

and

$$E_{ii} = S_i \cdot A_{ii}$$

The translog model allows these to vary at each data point, and the full table of elasticities is given in Appendix III.3. Tables III.2 and III.3 below give the averages of the partial elasticities of substitution and the price elasticities of demand.

Average Partial Elasticities of Substitution
Fuel Subsystem

TABLE III.2

	COAL	OIL	NUCLEAR FUEL
COAL	-0.599	1.0302	4.49
OIL		6.09	-22.66
NUCLEAR FUEL			23.25*

* Average of estimates from 1966/7 to 1982/3 all others averaged over the entire period

Note that since $\beta_{ij} = \beta_{ji}$, then $A_{ij} = A_{ji}$ and hence the structure of Table III.2.

Average Price Elasticities of Demand
Fuel Subsystem

TABLE III.3

	COAL	OIL	NUCLEAR FUEL
COAL	-0.431	0.196	0.231
OIL	0.778	0.818	-1.64
NUCLEAR FUEL	2.65*	4.11*	1.35*

* Average of estimates from 1966/7 to 1982/3; all others averaged over the entire period

Table III.3 should be read to give, for example, E_{CO} as 0.196 and E_{OC} as 0.778 and so on. The relatively tiny size of the nuclear fuel share in the early years of the sample has led to the initial estimates for some of the elasticities to be enormous; to avoid the bias which inclusion of such terms would give to the average, the nuclear fuel row is given with averages from 1966/7 when the nuclear fuel share rose above 5 percent. However, the earlier drawbacks inherent in the structure of these data apply forcefully here, and it is probable that these elasticities should be viewed as giving a fairly general picture of interfuel substitution possibilities.

III.2.3 Fuel Subsystem Results

The own-price elasticity of demand for coal is negative, as would be expected, and is inelastic which again would be expected given the major role in producing electricity taken by coal. The absolute value of this elasticity has increased slightly over the whole period, but rose substantially in the early 1970s to a maximum of 0.624 in 1974/5, declining consistently from then. However, the own-price elasticities for oil and nuclear fuel are both positive. Although the average elasticity for oil shows the demand to be inelastic, it has moved from 1.2 in 1963/4 to a low of 0.134 in 1974/5 from which it has risen consistently to 2.3 in 1982/3. Conversely the own-price elasticity for nuclear fuel has fallen consistently over the period and its average value of 1.35 greatly overstates its final year estimate of 0.42. The positive signs on these two elasticities can be justified given the CEGB's desire not to be dependent on coal for strategic reasons (3), and to increase the amount of electricity generated by nuclear power for both strategic and economic reasons. In this light rising fuel prices might still well be met by increasing the quantity of the fuel burnt, hence the positive sign.

This view is given further weight by the evidence on interfuel substitutability from the cross-price elasticities and partial elasticities of substitution. The values for E_{oc}, E_{co} and A_{co} are 0.78, 0.196 and 1.03 indicating that the two fuels have been substitutes over the period. Although the value of E_{co} is below its average in the years 1979/80 to 1982/3 the opposite is true for E_{oc} and A_{co}. Similarly the values for E_{cn}, E_{nc} and A_{cn} are 0.23, 2.65 and 4.49 which show substantially more substitutability than the previous case.

Finally the values for E_{on}, E_{no} and A_{on} are 4.11, -1.64 and -22.7. The negative figures are indicative of complementarity which would again bear out the argument that the CEGB's (stated) attempt to diversify its fuel inputs and expand its nuclear base. Oil fired stations commissioned prior to the 1973/4 events have been completed and are in operation and the AGR programme has largely come on stream. Thus, abstracting from the highly expensive oil fired plant which was shut when oil prices became untenable, this approach of the CEGB would imply complementarity between oil and nuclear and substitutability between coal and each of the other fuels. This is exactly what the results show.

The remaining task is to substitute the estimated coefficients into the fuel price equation to derive a fuel price index (discussed in the Theory section above; Chapter II). The equation is:

$$\log PF = \alpha_o + \sum_i \alpha_i \log PF_i + \tfrac{1}{2}\sum_{ij}\sum \beta_{ij} \log PF_i \cdot \log PF_j$$

which can now be estimated since all values are known except α_o which is set to the value which makes the index one in the base year. The fuel price index generated by this aggregator equation is given in Appendix III.4; it can now be used as an instrumental variable in the estimation of the translog cost equation defined over the prices of capital, labour and fuel in the second stage of the estimation.

III.2.4 The Complete Cost Function : Input Substitution Possibilities

The initial share equations in the complete system are:

$$\text{SHARE OF CAPITAL IN TOTAL INPUT EXPENDITURE (CAPITALSHARE)} = \alpha_K + \beta_{KQ} \log \text{OUTPUT} + \beta_{KK} \log \text{PRICE OF CAPITAL (PK)} + \beta_{KL} \log \text{PRICE OF LABOUR (PL)} + \beta_{KF} \log \text{PRICE OF FUEL (PF)}$$

$$\text{SHARE OF LABOUR IN TOTAL INPUT EXPENDITURE (LABOURSHARE)} = \alpha_L + \beta_{LQ} \log \text{OUTPUT} + \beta_{LK} \log \text{PRICE OF CAPITAL (PK)} + \beta_{LL} \log \text{PRICE OF LABOUR (PL)} + \beta_{LF} \log \text{PRICE OF FUEL (PF)}$$

$$\text{SHARE OF FUEL IN TOTAL INPUT EXPENDITURE (FUELSHARE)} = \alpha_F + \beta_{FQ} \log \text{OUTPUT} + \beta_{FK} \log \text{PRICE OF CAPITAL (PK)} + \beta_{FL} \log \text{PRICE OF LABOUR (PL)} + \beta_{FF} \log \text{PRICE OF FUEL (PF)}$$

Of these the capitalshare and labourshare equations were estimated, and a nested series of restrictions imposed; the coefficients in the fuelshare equations may be inferred from the estimated coefficients at any stage. Following Maddala (1979), the maximum likelihood technique in these circumstances is ordinary least squares which is the estimation method used.

As discussed in the Data section (above) there is a number of alternative possibilities to be used to represent the explanatory variables 'price of capital' and 'price of fuel'. In the latter case part of the purpose of estimating the fuel subsystem was to derive a consistent index of the price of fuel to be used as an instrumental variable in the estimation of the overall system. This index was derived and explained (above) and listed in Appendix III.4. Two other indices can also be constructed, following the example of Westoby and McGuire (1984). Their work also gives one means of deriving a price of capital; an alternative route to this variable was to use a published index on the price of capital. (These are noted in the Data section).

It is not clear, a priori, which of these possible alternatives is more viable. In the case of the index of fuel prices the three choices are

(i) IPF - the fuel price index derived by estimation of the fuel subsystem

(ii) PF - an index calculated using data on works cost of generation and on output from different fuels and total fuel used in tonnes of coal equivalent

(iii) APF - an index calculated from total fuel expenditure (derived in the fuel subsystem estimation) and total fuel used in tonnes of coal equivalent.

The correlation matrix between these is shown as Table III.4.

Correlation matrix : fuel price indices TABLE III.4

	IPF	PF	APF
IPF	1.00	-0.98803	-0.98447
PF		1.00	0.99932
APF			1.00

Clearly the procedures to generate the different indices have yielded very similar results.

There were two choices to represent the price of capital variable. PK1 was defined according to the method used by Westoby and McGuire; PK2 was based on the index for the price of capital published by the National Institute (N.I.E.S.R.), (and was almost identical to the index of Capital Prices published by the C.S.O.). The correlation coefficient between these was 0.84733, rather lower than those between the fuel price indices.

The choice of which variables to use was made on the basis of comparison of the results of regressions using each of the alternatives in turn. The clearest choice was to use PK1 as the results from PK2 were invariably worse. The decision on the fuel price index was, as anticipated from Table III.4, much more marginal, but in general the best results came from regressions using PF. Thus, all the estimations reported in the text use PK1 as the price of capital and PF as the price of fuel. The results of using the alternative specifications of these variables are given in Appendix III.5.

As was the case in estimating the fuel subsystem, it was anticipated that there would be a degree of multicollinearity between the explanatory variables. These were normalised by being expressed in index form, but there was inevitably some common time trend.

The correlation coefficients between the variables are shown in Table III.5.

Correlation Matrix : All explanatory variables TABLE III.5

	LPF	LIPL	LPK1	LIG
LPF	1.00	0.98748	0.86004	0.79015
LIPL		1.00	0.85290	0.85090
LPK1			1.00	0.68235
LIG				1.00

where

LPF = log of fuel price index PF

LIPL = log of index of price of labour

LPK1 = log of capital price index PK1

LIG = log of index of output

Table III.5 shows that the problems expected and encountered with the data for the fuel subsystem are likely to be less prominent in estimation of the overall function.

The results of estimating the initial share equations are:

$$\text{CAPITALSHARE} = 1.64 + 0.11 \log \text{OUTPUT} + 0.16 \log \text{PK1} - 0.05 \log \text{PL} - 0.12 \log \text{PF}$$

standard error	0.27	0.073	0.021	0.042	0.04
t statistic	6.03	1.48	7.53	-1.17	-3.1

$\bar{R}^2 = 0.98$ DW = 1.21 $F_{4\ 15} = 196.98$ SSR = 0.0037

$$\text{LABOURSHARE} = -0.28 - 0.068 \log \text{OUTPUT} - 0.098 \log \text{PK1} + 0.09 \log \text{PL} - 0.0028 \log \text{PF}$$

standard error	0.17	0.046	0.013	0.026	0.023
t statistic	-1.63	-1.49	-7.43	3.42	-0.12

$\bar{R}^2 = 0.97$ DW = 1.71 $F_{4\ 15} = 133.67$ SSR = 0.00144

The adjusted R^2 and $F_{4\ 15}$ statistics are both satisfactorily high (the tabular $F_{4\ 15}$ values being: $F^{0.05}_{4\ 15} = 3.06$ and $F^{0.01}_{4\ 15} = 4.89$). Five of the ten coefficients estimated are statistically significant at the 5 percent level. The Durbin Watson statistics both fall into the inconclusive region:

20 observations, 4 explanatory variables $d_L = 0.9$ $d_u = 1.83$

Capital share DW = 1.21 Labourshare = 1.17

Following the experience of estimating the fuel subsystem, the above equations were reestimated using the dummy variables established in that section. The full results are given in Appendix III.6 part I. The effects of adding the dummy variable were to make a tiny improvement to the adjusted R^2; to improve the Durbin Watson statistics (which, nevertheless, remained in the inconclusive region - a region which is very large given twenty observations and five explanatory variables); to reduce the F statistic slightly. The t statistic on the dummy variable is close to being statistically significant for the capitalshare equation but nowhere near for the labour share equation. It seems that the dummy variable which worked particularly well in helping to explain the fuel input mix, works markedly less well for the overall input determination.

Homotheticity is imposed by estimating the share equation without the output variable (the slope of any isoquant being determined only by marginal productivities and not by the level of output). The results are:

CAPITALSHARE =	2.01	+ 0.14 log PK	− 0.02 log PL	− 0.12 log PF
standard error	0.1	0.016	0.038	0.039
t statistic	20.1	8.53	-0.51	-3.2

$\overline{R}^2 = 0.975$ DW = 1.49 $F_{3\ 16} = 243.6$ SSR = 0.0042

LABOURSHARE =	-0.51	− 0.085 log PK	+ 0.071 log PL	+ 0.0018 log PF
standard error	0.063	0.01	0.023	0.024
t statistic	-8.2	-8.4	2.97	0.073

$\overline{R}^2 = 0.96$ DW = 1.52 $F_{3\ 16} = 164.9$ SSR = 0.0017

The adjusted R^2 statistic and F statistic remain high ($F^{0.05}_{3\ 16} = 3.24$) and six of the eight estimated coefficients are statistically significant at the 5 percent level. The Durbin Watson statistics both lie in the inconclusive range:

20 observations, 3 explanatory variables $d_L = 1.00$ $d_u = 1.68$

Capitalshare DW = 1.49; Labourshare DW = 1.52

The effect of dropping the output variable has been marginally to worsen some of the statistics - the adjusted R^2 and the SSR. But the coefficient on (log Output) was not significant in any of the first set of regressions and the fall in the adjusted R^2 was to be expected. From the correlation matrix of the explanatory variables (Table III.4) it is clear that adding the output variable to the above equations is likely to result in some increased multicollinearity, and probably a rise in $\overline{R}^2$. The F statistic improves when output is dropped, as do the Durbin Watson statistics. Clearly output is a probable source of serial correlation (which remains evident in the results) and so dropping it improves the Durbin Watson statistics. The restriction here is only on one coeffient (the null hypothesis being that $\beta_{KQ} = \beta_{LQ} = 0$) so an F test on the restricted and unrestricted equations is unnecessary and it is equivalent to the t test of the significance of β_{KQ} and β_{LQ}. However if it is carried out:

$$F^* = \frac{(0.0059 - 0.00514)/2}{0.00514/30}$$

$$= 2.22$$

The tabular F value is $F^{0.05}_{2\ 30} = 3.32$; thus $F^* < F$, and the null hypothesis that the coefficient on output is zero may be accepted.

[Once again these equations were reestimated with the dummy variable included (see Appendix III.6 part 2). The only improvement to the results is seen in the Durbin Watson statistics; that from the capitalshare equation lies in the no autocorrelation region, that from labourshare remains inconclusive.]

Although dropping the output variable is an accepted restriction, there are still two coefficients (on PL in capitalshare and on PF in labourshare) which remain not significant. (Adding the dummy variable makes a slight improvement but does not switch anything from not significant to significant. The coefficients on the dummy variables are themselves not significant).

The next stage in this process is to impose the restriction of linear homogeneity, that the sum of the coefficients on the explanatory variables is zero ($\sum \beta_{ij} = 0, \ _{ij} = K, L, F$). The results are:

$$\text{CAPITALSHARE} = 2.04 + 0.14 \log \left[\frac{PK}{PF} \right] - 0.012 \log \left[\frac{PL}{PF} \right]$$

Standard error	0.05	0.005	0.027
t statistic	40.8	27.8	-0.42

$\bar{R}^2 = 0.976$ DW $= 1.46$ $F_{2\ 17} = 385.99$ SSR 0.0043

$$\text{LABOURSHARE} = -0.44 - 0.072 \log \left[\frac{PK}{PF} \right] + 0.093 \log \left[\frac{PL}{PF} \right]$$

Standard error	0.033	0.0034	0.018
t statistic	13.4	21.34	5.2

$\bar{R}^2 = 0.961$ DW $= 1.54$ $F_{2\ 17} = 235.3$ SSR 0.0018

The adjusted R^2 statistics remain approximately the same, the F statistics increase in both equations. There is also an improvement in the Durbin Watson statistics:

20 observations, 2 explanatory variables $d_L = 1.10$ $d_u = 1.54$

Capitalshare DW = 1.46, Labourshare DW = 1.54

The capitalshare equation remains in the inconclusive region, but the labourshare equation is exactly on the upper value of 1.54. The only coefficient not to be statistically significant is that on log $[^{PL}/_{PF}]$ in the capitalshare equation, the other t statistics are all quite large.

Inspection of the residuals from each equation shows no particularly obvious example of serial correlation, however there are common outliers in the residuals. These occur for the years 1973/4, 1974/5, 1979/80 and 1982/3. The special features of the first three of these years led to them being included in the dummy variable. However reestimating the equations with the dummy makes no appreciable improvement and the coefficient on the dummy is not significant in either case (results given in Appendix III.6 part 3).

The acceptability of the linear homogeneity is checked with an F test:

$$F^* = \frac{(0.0061 - 0.0059)/2}{(0.0059)/32}$$

$$= 0.54$$

The tabular F value is $F^{0.05}_{2\ 32} \cong 3.32$ and as $F^* < F$, the null hypothesis that the restrictions of linear homogeneity are true may be accepted.

The final restriction to be imposed is symmetry: $\beta_{KL} = \beta_{LK}$ (and so on). Again this is accomplished by stacking the regressions as was undertaken for the fuel subsystem. The results are:

CAPITALSHARE	$= 2.01$	$+ 0.143 \log \left[\frac{PK}{PF}\right]$	$- 0.07 \log \left[\frac{PL}{PF}\right]$
Standard error	0.04	0.005	0.005
t statistic	45.7	30.6	15.3

LABOURSHARE	$= -0.42$	$-0.07 \log \left[\frac{PK}{PF} \right]$	$+ 0.09 \log \left[\frac{PL}{PF} \right]$
Standard error	0.045	0.005	0.025
t statistic	-9.3	15.3	3.67

$\overline{R}^2 = 0.997$ DW $= 1.104$ $F_{4\ 35} = 3701.0$ SSR 0.0073

All coefficients are now statistically significant and the adjusted R^2 and F statistics are both very large. However, the Durbin Watson statistic now shows positive autocorrelation:

40 observations, 3 explanatory variables $d_L = 1.34$, $d_u = 1.66$

Computed DW = 1.104

As in the previous cases the equation was reestimated using the dummy variable (results shown in Appendix III.6 part 4). The effect is to bring the Durbin Watson statistic just into the inconclusive range (at 1.3 compared to a lower value of $d_L = 1.29$). The coefficient on the dummy in the capitalshare equation is just significant, that in the labourshare equation very far from being significant. Not surprisingly, an F test of the hypothesis that the coefficients on the dummy variables are both zero is accepted:

$$F^* = \frac{(0.0073 - 0.0064)/2}{(0.0064)/32}$$

$$= 2.25$$

$F^{0.05}_{2\ 32} \cong 3.3$ and $F^* < F$ so the restriction may be accepted. In addition the coefficients on the other explanatory variable are virtually identical to those reported above; hence, there is no obvious case for choosing to use the results of the regression incorporating the dummy variable.

The problem of autocorrelation still remains. One means of dealing with first order serial correlation is to use the Cochran-Orcutt procedure, and the stacked regression was so reestimated. The results are given in Appendix III.6 part 5, but it is clear that this has not helped. The Durbin Watson statistic does not improve sufficiently to take it out of the positive autocorrelation region (despite being biased by the estimation procedure towards 2); the adjusted R^2 and F statistics deteriorate. Accordingly, these results do not justify departing from those above.

The symmetry restriction is tested:

$$F^* = \frac{(0.0073 - 0.0061)}{(0.0061)/34} = 6.69$$

The tabular F value is $F^{0.05}_{1\ 34} \cong 4.1$, thus $F^* > F$. This implies that the hypothesis that the symmetry restriction is true must be rejected, precisely the result that occurred in the fuel subsystem estimation. Just as in that case the rejection of symmetry was overruled, so it is here. This analysis is similar to that of Westoby and McGuire (1984) who impose symmetry a priori (with no further explanation or justification). Similarly Hunt (1984) finds symmetry rejected but imposes it. A not unreasonable conclusion is that since the theoretical model so clearly requires symmetry, the rejection of the restriction by the applied econometrics may be more to do with the quality of the data, the precise specification of the explanatory variables or the acceptability of the assumption of neo-classical cost-minimising behaviour by the industry under consideration.

Consequently the coefficients estimated with the restrictions of linear homogeneity and symmetry imposed are used. Firstly the complete set of coefficients is calculated using the restrictions:

$$\sum \alpha_i = 1$$

$$\sum \beta_{ij} = 0 \qquad i, j = K, L, F$$

$$\beta_{ij} = \beta_{ji} \qquad i, j = K, L, F$$

The coefficients are listed in Appendix III.7.

The full set of coefficients may now be used to calculate the Allen partial elasticities of substitution and the own- and cross-price elasticities of demand using the formulae given in the theory section above (Chapter II). The translog model allows these elasticities to vary at each observation and the full list is given in Appendix III.8. Tables III.6 and III.7 below, give the average value of each elasticity:

Average Partial Elasticities of Substitution (Aij) Complete Model

TABLE III.6

	Capital	Labour	Fuel
Capital	-0.134	0.406	-0.136
Labour		-1.34	-0.67
Fuel			5.15

Average Own- and Cross- Price Elasticities of Demand (Eij)
Complete Model

TABLE III.7

	Capital	Labour	Fuel
Capital	-0.083	0.078	0.006
Labour	0.279	-0.264	-0.013
Fuel	-0.138	-0.054	0.21

III.2.5 Complete Cost Function Results

The own-price elasticities for both capital and labour are negative as would be predicted. The absolute value of the capital elasticity is very small indicating demand to be very inelastic; that for labour is also indicative of inelastic demand. The own-price fuel elasticity is small (inelastic) but positive. This apparently counter-intuitive result might be explained by noting that the CEGB has a statutory requirement to meet electricity demand and has, over the first ten years of the sample, been faced with rapidly rising demand. Demand has still grown, albeit inconsistently and at a much smaller rate, since 1973/4. In these circumstances the CEGB may have been forced to increase its overall fuel input despite rising real prices, hence appearing to operate with a positive price elasticity of demand. However, it is also the case that 'wrong' signs for the elasticity may be the result of the translog cost function failing to confirm to a well-behaved production process at each data point. If so, then, as with the fuel subsystem, the results should not be treated as being especially robust.

The capital/fuel elasticities, E_{KF}, E_{FK} and A_{KF} are 0.006, -0.138 and -0.136 respectively. The two negative signs indicate complementarity which corresponds with the results reported. Conversely the capital/labour elasticities (E_{KL}, E_{LK} A_{KL} : 0.078, 0.279, 0.406) are all positive and hence show substitutability between the two factors. This certainly corresponds to the observed experience of the industry; generating capacity has risen together with the average size of generating sets while the number of employees has fallen consistently since 1966/7, see Fig III.4. Clearly the capital-labour ratio has increased over the period and the substitutability result thus fits in with the expected result. Again it corresponds to the results reported. Finally the labour/fuel elasticities (E_{FL}, E_{LF}, A_{LF} : -0.054, -0.013, -0.67) are all negative, implying that the factors are complements. Inspection of the series of elasticities given in Appendix III.8 shows that each of the fuel related elasticities changes sign after the year 1973/4 being either positive until that date and negative thereafter, or vice versa. This is the year of the first major oil price rise; it (almost) invariably produced an outlier in the residuals of each regression, and represents a structural shift right across the economy. The CEGB use of oil changed dramatically within two years (13.756 M.tonnes in 1973/4 to 9.572 M.tonnes 1975/6 (4)), while the works cost per kWh in conventional steam stations rose rapidly (0.4829p/kWh in 1973/4 to 0.7583p/kWh 1974/5 to 0.9504p/kWh 1975/6(4)). The share of fuel in total expenditure on inputs in the years 1971/2 to 1973/4 was 9.6%, 9.4% and 8.9%. For the next five years it rose markedly : 11%, 16%, 16%, 17%, 18%, to stabilise at approximately that level.

Because of this noticeable break, the sample was split into two periods, 1963/4 to 1973/4 and 1974/5 to 1982/3, and the elasticities averaged for each period. These results are presented in Tables III.8a, III.6 and III19a, III19b.

The own-price elasticities of each input are all negative in the second period and in absolute terms larger than those estimated for the entire period and (with the exception of fuel) for the first period. The second period own-price elasticities are all between 0 and -1 and rank capital as having the most inelastic demand, then fuel, then labour.

Average Partial Elasticities of Substitution
Complete Model

TABLE III.8

	Capital	Labour	Fuel
Capital	-0.043	0.35	-0.465
Labour		-1.07	-1.56
Fuel			10.6

Table III.8a : 1963/4 - 1973/4

	Capital	Labour	Fuel
Capital	-0.244	0.477	0.266
Labour		-1.67	0.411
Fuel			-1.5

Table III.8b : 1974/5 - 1982/3

Average Own- and Cross-Price Elasticities of Demand Complete Model

TABLE III.9

	Capital	Labour	Fuel
Capital	-0.03	0.055	-0.026
Labour	0.266	-0.184	-0.082
Fuel	-0.38	-0.17	0.56

Table III.9a : 1963/4 - 1973/4

	Capital	Labour	Fuel
Capital	-0.148	0.107	0.045
Labour	0.295	-0.36	0.071
Fuel	0.16	0.094	-0.254

Table III.9b : 1974/5 - 1982/3

In the second period each of the own-elasticities is negative; all others are positive. The implication is that in that period each factor become substitutable for the others. The changing signs of the elasticities are shown in Table III.10.

Signs of the Elasticities in Each Period Complete Model

TABLE III.10

	E_{KK}	E_{LL}	E_{FF}	E_{KF}	E_{FK}	A_{FK}	E_{KL}	E_{LK}	A_{LK}	E_{FL}	E_{LF}	A_{LF}
1963/4 – 1982/3	–	–	+	+	–	–	+	+	+	–	–	–
1963/4 – 1973/4	–	–	+	–	–	–	+	+	+	–	–	–
1974/5 – 1982/3	–	–	–	+	+	+	+	+	+	+	+	+

The negative sign on the own-price elasticity of fuel in the second period may be an indication that as the growth in demand for energy generating in the economy declined after 1973/4, and the total annual output of the CEGB remained fairly stable, the expected form of elasticity asserted itself.

The capital/labour substitutability result holds over all periods and is explained above. The significant change in the capital - labour ratio over the sample period is itself evidence of that substitutability. However, the other input combinations, Capital - Fuel and Labour - Fuel appear as complements for the entire and first periods but as substitutes for the second period. The capital - fuel complementarity result is also found by Westoby and McGuire for the electricity industry and by Hunt for the UK industrial sector, although, as noted in II.4 above, that substitutability has been found by Pindyck (1979) and by Griffin and Gregory (1976). It seems quite probable that the shocks to the energy economy commencing in 1973/4 have brought about a shift in consumer and producer behaviour. As a result the entire period results may not be entirely trustworthy; equally, however, the second period results quoted here run for a sample of only nine observations and conclusions based on them should, perhaps, not be pushed too far yet.

III.3 SUMMARY

Given the limitations of the data and of the sample size, it has, nevertheless, proved possible to fit a translog cost model to electricity production by the CEGB in a two stage procedure. The first stage analysed the fuel input mix as a separable component of the overall cost function. The relevant inputs were taken to be coal, oil and nuclear fuel and the estimates from the model permitted discussion of inter fuel substitution possibilities and the calculation of a fuel price index.

The second stage estimated a translog cost function in which the regressors were the prices of capital, labour and fuel. The results provided estimates of the degree of substitutability between pairs of factors. A particularly interesting result is evidence that substitutability has increased since the oil price shock of 1973/4. Where pairs of factors were already substitutes, their degree of substitutability has risen; where pairs of factors were complements they become substitutes for the 1974/5 - 1982/3 period. A significantly longer time period is required to test the robustness of these results, particularly in the light of the recent decline in the real prices of oil and energy generally.

APPENDIX III.1

ALTERNATIVE FUEL SUBSYSTEM ESTIMATION

Results of estimating the stacked regression (imposing linear homogeneity and symmetry) using the Cochrane-Orcutt procedure.

(i) Without dummy variable

$$\text{COALSHARE} = 0.799 - 0.033 \log \left[\frac{\text{PCOAL}}{\text{PNF}}\right] + 0.0033 \log \left[\frac{\text{POIL}}{\text{PNF}}\right]$$

Standard error	0.045	0.055	0.0027
t statistic	17.64	-0.61	1.23

$$\text{OILSHARE} = 0.092 + 0.0033 \log \left[\frac{\text{PCOAL}}{\text{PNF}}\right] + 0.12 \log \left[\frac{\text{POIL}}{\text{PNF}}\right]$$

Standard error	0.05	0.0027	0.046
t statistic	1.83	1.23	2.52

$\bar{R}^2 = 0.922$ DW = 1.47 $F_{4\ 35} = 106.4$ SSR 0.0514

= 0.872 (s.e = 0.073; t = 11.89)

(ii) With dummy variable

$$\text{COALSHARE} = 0.808 - 0.041\text{D} - 0.086 \log \left[\frac{\text{PCOAL}}{\text{PNF}}\right] + 0.00028 \log \left[\frac{\text{POIL}}{\text{PNF}}\right]$$

Standard error	0.37	0.013	0.049	0.0025
t statistic	22.1	-3.16	-1.76	0.112

$$\text{OILSHARE} = 0.093 + 0.37\text{ D} + 0.00028 \log \left[\frac{\text{PCOAL}}{\text{PNF}}\right] + 0.131 \log \left[\frac{\text{POIL}}{\text{PNF}}\right]$$

Standard error	0.041	0.014	0.0025	0.039
t statistic	2.28	2.66	0.112	3.34

$\bar{R}^2 = 0.95$ DW = 1.665 $F_{6\ 33} = 107.45$ SSR 0.0338

= 0.864 (s.e. = 0.082; t = 10.57)

APPENDIX III.2

ESTIMATED AND INFERRED COEFFICIENTS; FUEL SUBSYSTEM

	Linear Homogeneity	Homogeneity/Symmetry
β_c	0.91 (28.1)	0.822 (35.1)
β_o	0.023 (0.78)	0.018 (0.5)
β_n	[0.067]	[0.16]
β_{cc}	0.022 (0.34)	-0.13 (-2.42)
β_{co}	-0.25 (-3.4)	0.0032 (0.7)
β_{cn}	[0.228]	[0.1248]
β_{oc}	0.098 (1.67)	0.0032 (0.7)
β_{oo}	0.193 (2.94)	0.27 (4.41)
β_{on}	[-0.291]	[-0.2732]
β_{nc}	[-0.12]	[0.1248]
β_{no}	[-0.057]	[-0.2732]
β_{nn}	[-0.519]	[0.1484]
D_c	-0.09 (4.1)	-0.103 (-4.24)
D_o	0.086 (4.34)	0.075 (3.11)

[ ] indicate coefficient was calculated indirectly from the estimated coefficients

( ) t statistic

APPENDIX III.3

1. OWN- AND CROSS-PRICE ELASTICITIES OF DEMAND; FUEL SUBSYSTEM

	E_{CC}	E_{OO}	E_{NN}	E_{CO}	E_{CN}	E_{OC}	E_{ON}	E_{NC}	E_{NO}
1963/4	-0.296	1.2	8.74	0.133	0.165	0.882	-2.03	9.41	-17.5
1964/5	-0.305	1.1	8.74	0.142	0.151	0.87	-2.03	9.17	-18.7
1965/6	-0.280	1.1	3.57	0.141	0.154	0.85	-1.88	4.4	-7.35
1966/7	-0.36	1.07	1.91	0.151	0.206	0.824	-1.72	3.18	-4.9
1967/8	-0.362	1.01	1.65	0.147	0.211	0.822	-1.89	2.96	-4.74
1968/9	-0.345	1.26	1.6	0.131	0.212	0.84	-2.2	2.98	-4.83
1969/70	-0.379	0.84	1.91	0.165	0.21	0.807	-1.72	3.18	-5.34
1970/1	-0.476	0.37	2.02	0.248	0.229	0.72	-1.1	3.24	-5.3
1971/2	-0.51	0.27	2.02	0.276	0.234	0.753	-0.93	3.18	-5.2
1972/3	-0.52	0.27	1.76	0.276	0.24	0.746	-0.95	2.95	-4.66
1973/4	-0.597	0.15	1.76	0.336	0.257	0.679	-0.78	2.87	-4.7
1974/5	-0.624	0.134	2.06	0.362	0.26	0.603	-0.74	3.15	-5.4
1975/6	-0.553	0.36	1.52	0.248	0.24	0.711	-1.09	2.82	-4.5
1976/7	-0.474	0.53	0.8	0.209	0.262	0.726	-1.23	2.14	-2.89
1977/8	-0.493	0.41	0.97	0.233	0.26	0.708	-1.1	2.3	-3.2
1978/9	-0.474	0.55	0.74	0.203	0.27	0.726	-1.31	2.07	-2.81
1979/80	-0.431	0.86	0.54	0.161	0.27	0.762	-1.6	1.96	-2.53
1980/1	-0.372	1.32	0.8	0.138	0.245	0.897	-2.07	2.23	-2.88
1981/2	-0.399	1.26	0.54	0.129	0.266	0.796	-2.74	1.97	-3.29
1982/3	-0.359	2.3	0.42	0.087	0.268	0.843	-3.74	1.91	-2.75
a	-0.431	0.818	2.204	0.196	0.231	0.778	-1.64	3.40	-5.67
b			1.35					2.65	-4.11

a = average of all twenty estimates

b = average of estimates from 1966/7 to 1982/3

2. PARTIAL ELASTICITIES OF SUBSTITUTION; FUEL SYBSYSTEM

	σ_{CC}	σ_{OO}	σ_{NN}	σ_{CO}	σ_{CN}	σ_{ON}
1963/4	-0.345	9.29	582.6	1.029	10.98	-135.6
1964/5	-0.36	7.95	582.6	1.027	10.83	-135.6
1965/6	-0.399	8.0	102.0	1.028	5.3	-53.64
1966/7	-0.449	7.25	36.7	1.027	3.97	-33.15
1967/8	-0.453	7.05	28.9	1.028	3.7	-33.15
1968/9	-0.423	9.9	27.4	1.031	3.66	-38.03
1969/70	-0.481	5.19	36.7	1.025	4.04	-33.15
1970/1	-0.673	1.5	40.4	1.019	4.57	-21.77
1971/2	-0.75	0.99	40.4	1.017	4.67	-18.51
1972/3	-0.771	0.99	32.0	1.017	4.37	-17.2
1973/4	-0.973	0.45	32.0	1.016	4.67	-14.18
1974/5	-1.051	0.375	42.1	1.015	5.3	-15.1
1975/6	-0.792	1.46	25.7	1.019	4.04	-18.51
1976/7	-0.667	2.6	9.21	1.022	3.01	-14.18
1977/8	-0.710	1.81	12.46	1.02	3.31	-14.18
1978/9	-0.667	2.8	8.0	1.023	2.92	-14.18
1979/80	-0.582	5.5	5.3	1.028	2.64	-16.1
1980/1	-0.470	10.9	9.2	1.132	2.81	-23.8
1981/2	-0.517	10.1	5.2	1.033	2.56	-26.3
1982/3	-0.446	27.7	3.7	1.048	2.37	-33.1
a	-0.599	6.09	83.13	1.0302	4.49	-35.5
b			23.26			-22.66

a = average of all twenty estimates

b = average of estimates from 1966/7 to 1982/3

APPENDIX III.4

FUEL PRICE INDEX

Derived from: fuel prices
estimated coefficients (Appendix III.2)
and the equation:

$$\log PF = \alpha_0 + \sum_i \alpha_i \log PF_i + \tfrac{1}{2}\sum_{ij}\sum \beta_{ij} \log PF_i \log PF_j$$

	a	b
1963/4	1.00	6.11
1964/5	1.04	6.22
1965/6	1.35	6.46
1966/7	1.02	6.13
1967/8	0.90	6.02
1968/9	0.93	6.05
1969/70	1.02	6.14
1970/1	0.61	5.27
1971/2	0.68	5.8
1972/3	0.69	5.8
1973/4	-0.02	5.08
1974/5	-0.84	4.27
1975/6	-1.36	3.75
1976/7	-1.93	3.18
1977/8	-2.07	3.04
1978/9	-2.30	2.81
1979/80	-3.02	2.09
1980/1	-3.43	1.68
1981/2	-4.11	1.00
1982/3	-4.11	1.00

a = base year 1963/4 b = base year 1982/3

APPENDIX III.5

REGRESSION RESULTS WITH ALTERNATIVE DEFINITIONS OF EXPLANATORY VARIABLES

	KSH	LSH	KSH	LSH	KSH	LSH
C	2.44 (0.62) (3.95)	-0.8 (0.38) (-2.19)	1.23 (0.28) (4.4)	-0.28 (0.16) (-1.8)	2.3 (0.43) (5.4)	-0.91 (0.25) (-3.6)
LIG	-0.274 (0.14) (-1.88)	0.19 (0.09) (2.07)	0.078 (0.085) (0.91)	-0.07 (0.048) (-1.5)	-0.09 (0.17) (-0.53)	0.074 (0.1) (0.73)
LPK_1			0.17 (0.026) (6.34)	-0.097 (0.015) (-6.6)		
LPK_2	0.026 (0.199) (0.13)	-0.057 (0.121) (-0.46)			-0.11 (0.15) -(0.73)	-0.0095 (0.089) (-0.106)
LIPL	-0.08 (0.1) (-0.8)	0.12 (0.063) (1.9)	-0.08 (0.043) (-1.87)	0.089 (0.024) (3.7)	-0.105 (0.098) (-1.07)	0.13 (0.058) (2.28)
LPF	-0.012 (0.13) (-0.96)	-0.045 (0.079) (-0.57)				
LIPF			0.036 (0.016) (2.21)	0.0012 (0.0092) (0.13)	-0.04 (0.034) (-1.2)	0.035 (0.019) (1.77)
LAPF						
$\bar{R}^2$	0.89	0.84	0.97	0.965	0.897	0.86
DW	1.52	1.55	0.92	1.17	1.72	1.79
F	38.33	26	159.9	133.7	42.35	31.4
SSR	0.018	0.0067	0.0045	0.00144	0.016	0.0056

KSH = Capitalshare
LSH = Labourshare
LIG = log of index of output
LPK_1 = log of price of capital index (Westoby and McGuire [1984])
LPK_2 = log of price of capital index (N.I.E.S.R.)
LIPL = log of index of price of labour
LPF = log of fuel price index (log of PF) }
LIPF = log of fuel price index (log of IPF) } discussed in main text
LAPF = log of fuel price index (log of APF) }

(Appendix III.5 Continued)

	KSH	LSH	KSH	LSH	KSH	LSH	KSH	LSH
C	1.59 (0.25) (6.3)	-0.29 (0.16) (-1.7)	2.47 (0.56) (4.4)	-0.9 (0.35) (-2.5)	1.94 (0.08) (24.8)	-0.52 (0.05) (-10.12)	1.4 (0.15) (9.47)	-0.16 (0.09) (-1.8)
LIG	0.10 (0.07) (1.45)	-0.067 (0.046) (-1.47)	-0.29 (0.15) (-1.96)	0.19 (0.09) (2.11)				
LPK_1	0.16 (0.02) (7.95)	-0.099 (0.013) (-7.5)			0.14 (0.016) (9.03)	-0.09 (0.01) (-8.4)		
LPK_2			0.04 (0.19) (0.21)	-0.07 (0.1) (-0.57)			-0.17 (0.17) (-1.0)	0.07 (0.11) (0.69)
LIPL	-0.05 (0.04) (-1.43)	0.086 (0.024) (3.55)	-0.08 (0.1) (-0.8)	0.12 (0.06) (1.9)	-0.02 (0.03) (-0.8)	0.07 (0.02) (3.2)	-0.12 (0.11) (-1.15)	0.14 (0.07) (2.14)
LPF								
LIPF								
LAPF	-0.107 (0.03) (-3.4)	0.0007 (0.02) (0.04)	-0.02 (0.1) (-0.2)	-0.034 (0.065) (-0.5)	-0.11 (0.03) (3.6)	0.005 (0.021) (0.25)	0.14 (0.074) (1.84)	-0.14 (0.05) (-2.99)
$\bar{R}^2$	0.98	0.97	0.89	0.84	0.98	0.96	0.87	0.81
DW	1.17	1.18	1.52	1.56	1.45	1.53	1.4	1.3
F	215.5	133.6	38.4	25.9	268.1	165.5	42.4	27.2
SSR	0.0034	0.0014	0.018	0.007	0.0038	0.0016	0.022	0.009

The figures in round brackets: (standard error)
(t statistic)

(Appendix III.5 Continued)

	KSH	LSH	KSH	LSH	KSH	LSH
C	1.3 (0.11) (11.45)	-0.056 (0.07) (-0.78)	1.45 (0.14) (10.4)	-0.49 (0.082) (-5.9)	2.16 (0.3) (6.9)	-0.78 (0.19) (-4.22)
LIG						
LPK$_1$			0.16 (0.023) (6.63)	-0.088 (0.014) (-6.4)		
LPK$_2$	-0.19 (0.17) (-1.12)	0.092 (0.11) (0.85)			-0.15 (0.12) (-1.23)	0.026 (0.074) (0.35)
LIPL	-0.13 (0.105) (-1.26)	0.15 (0.066) (2.32)	-0.055 (0.032) (-1.7)	0.066 (0.019) (3.5)	-0.12 (0.092) (-1.31)	0.14 (0.055) (2.64)
LPF	0.17 (0.089) (1.93)	-0.17 (0.056) (-3.04)				
LIPF			0.041 (0.015) (2.66)	-0.003 (0.009) (-0.33)	0.06 (0.017) (-3.2)	0.05 (0.01) (4.58)
LAPF						
$\bar{R}^2$	0.87	0.807	0.97	0.96	0.91	0.87
DW	1.34	1.27	1.07	1.5	1.74	1.79
F	43.1	27.6	215.12	166.0	59.0	42.9
SSR	0.0217	0.0086	0.0048	0.0016	0.016	0.0058

APPENDIX III.6

REGRESSION RESULTS FOR THE COMPLETE COST FUNCTION, INCORPORATING THE DUMMY VARIABLE

PART 1

CAPITALSHARE	=	1.66	+ 0.014D	+ 0.102 log OUTPUT	+ 0.16 log PK_1	− 0.063 log PL	− 0.104 log PF
Standard error		0.26	0.0087	0.07	0.02	0.041	0.037
t statistic		6.39	1.58	1.46	7.69	−1.54	−2.83

$\bar{R}^2 = 0.978$ DW = 1.54 $F_{5\ 14} = 173.7$ SSR = 0.00313

LABOURSHARE	=	−0.28	− 0.0053D	− 0.066 log OUTPUT	− 0.097 log PK_1	+ 0.095 log PL	− 0.0073 log PF
Standard error		0.17	0.0058	0.046	0.013	0.027	0.024
t statistic		−1.66	−0.92	−1.43	−7.27	3.52	−0.3

$\bar{R}^2 = 0.97$ DW = 1.33 $F_{5\ 14} = 106.053$ SSR = 0.0014

PART 2

CAPITALSHARE	=	2.01	+ 0.014D	+ 0.14 log PK_1	− 0.036 log PL	− 0.11 log PF
Standard error		0.096	0.009	0.015	0.038	0.038
t statistic		20.99	1.6	8.77	−0.94	−2.91

$\bar{R}^2 = 0.977$ DW = 1.86 $F_{4\ 15} = 201.4$ SSR = 0.0036

LABOURSHARE	=	−0.51	− 0.0058D	− 0.084 log PK_1	+ 0.77 log PL	− 0.0034 log PF
Standard error		0.063	0.006	0.01	0.025	0.025
t statistic		−8.13	−0.97	−8.27	3.12	−0.14

$\bar{R}^2 = 0.96$ DW = 1.71 $F_{4\ 15} = 123.5$ SSR = 0.0016

(Appendix III.6 Continued)

PART 3

CAPITALSHARE =	2.07	− 0.013D	+ 0.15 log [PK/PF]	− 0.017 log [PL/PF]
Standard error	0.051	0.0086	0.0054	0.026
t statistic	40.64	1.51	26.96	−0.65

$\bar{R}^2 = 0.98$ DW = 1.73 $F_{3\ 16} = 277$ SSR = 0.00372

LABOURSHARE =	−0.45	− 0.007D	− 0.074 log [PK/PF]	+ 0.096 log [PL/PF]
Standard error	0.034	0.0058	0.0036	0.018
t statistic	13.35	−1.26	20.4	5.4

$\bar{R}^2 = 0.962$ DW = 1.76 $F_{3\ 16} = 162.9$ SSR = 0.0017

PART 4

CAPITALSHARE =	2.04	+ 0.016D	+ 0.15 log [PK/PF]	− 0.07 log [PL/PF]
Standard error	0.045	0.0078	0.005	0.0048
t statistic	45.01	2.01	30.0	−14.78

LABOURSHARE =	−0.43	− 0.0064D	− 0.071 log [PK/PF]	+ 0.093 log [PL/PF]
Standard error	0.0456	0.0078	0.0048	0.024
t statistic	−9.5	−0.8	−14.78	3.88

$\bar{R}^2 = 0.998$ DW = 1.3 $F_{6\ 33} = 2654.2$ SSR = 0.0064

PART 5

(i) Without Dummy; Cochrane-Orcutt

CAPITALSHARE =	2.34	+ 0.18 log [PK/PF]	− 0.105 log [PL/PF]
Standard error	0.12	0.012	0.01
t statistic	19.68	14.8	−9.5

LABOURSHARE =	−0.76	− 0.105 log [PK/PF]	+ 0.12 log [PL/PF]
Standard error	0.11	0.01	0.025
t statistic	−7.1	−9.5	4.63

$\bar{R}^2 = 0.988$ DW = 1.26 $F_{4\ 35} = 763.5$ SSR = 0.0044

= 0.945 (0.043; 22.2)

(Appendix III.6 Continued)

(ii) With Dummy; Cochrane-Orcutt

CAPITALSHARE	= 2.33	+ 0.0047D	+ 0.18 $\log [{}^{PK}/PF]$	− 0.105 $\log [{}^{PL}/PF]$
Standard error	0.12	0.0052	0.012	0.011
t statistic	19.38	(0.90)	14.6	−9.4

LABOURSHARE	= −0.76	− 0.0015D	+ 0.105 $\log [{}^{PK}/PF]$	+ 0.12 $\log [{}^{PL}/PF]$
Standard error	0.11	0.0054	0.011	0.027
t statistic	−6.97	−0.27	−9.4	4.49

$\overline{R}^2 = 0.988$ DW = 1.31 $F_{6\ 33} = 494.9$ SSR = 0.0043

= 0.94 (0.045; 21.0)

APPENDIX III.7

ESTIMATED AND INFERRED COEFFICIENTS; COMPLETE MODEL

	Linear Homogeneity	Homogeneity/Symmetry
α_K	2.04 (40.8)	2.01 (45.7)
α_L	-0.44 (13.4)	-0.42 (-9.3)
α_F	[-0.6]	[-0.968]
β_{KK}	0.14 (27.8)	0.143 (30.6)
β_{KL}	-0.012 (-0.42)	-0.07 (15.13)
β_{KF}	[-0.128]	[-0.073]
β_{LK}	-0.072 (21.34)	-0.07 (15.13)
β_{LL}	0.093 (5.2)	0.09 (3.67)
β_{LF}	[-0.021]	[-0.02]
β_{FK}	[-0.068]	[-0.073]
β_{FL}	[-0.081]	[-0.02]
β_{FF}	[0.149]	[0.093]

[ ] indicate coefficient was calculated indirectly from the estimated coefficients

( ) t statistic

APPENDIX III.8

1. OWN- AND CROSS-PRICE ELASTICITIES OF DEMAND; COMPLETE MODEL

	E_{KK}	E_{LL}	E_{FF}	E_{KL}	E_{KF}	E_{LK}	E_{LF}	E_{FK}	E_{FL}
1963/4	0.02	0.03	0.84	0.01	-0.03	0.12	-0.16	-0.55	-0.29
1964/5	0.016	-0.03	0.91	0.02	-0.04	0.17	-0.14	-0.61	-0.30
1965/6	0.02	-0.02	1.11	0.02	-0.04	0.17	-0.15	-0.77	-0.34
1966/7	0.01	-0.08	0.95	0.03	-0.04	0.22	-0.13	-0.65	-0.30
1967/8	0.01	-0.08	0.91	0.03	-0.04	0.21	-0.13	-0.62	-0.29
1968/9	-0.01	-0.17	0.59	0.04	-0.03	0.26	-0.10	-0.39	-0.20
1969/70	-0.05	-0.29	0.36	0.07	-0.02	0.34	-0.05	-0.25	-0.11
1970/1	-0.07	-0.31	0.19	0.08	-0.02	0.34	-0.03	-0.13	-0.06
1971/2	-0.10	-0.36	0.07	0.11	-0.01	0.36	0.00	-0.06	0.00
1972/3	-0.10	-0.36	0.08	0.11	-0.01	0.36	0.00	-0.08	0.00
1973/4	-0.08	-0.34	0.13	0.09	-0.01	0.35	-0.02	-0.10	-0.03
1974/5	-0.08	-0.31	-0.04	0.08	0.01	0.32	0.00	0.05	-0.01
1975/6	-0.17	-0.39	-0.26	0.13	0.04	0.31	0.08	0.14	0.12
1976/7	-0.15	-0.37	-0.26	0.11	0.04	0.30	0.07	0.16	0.10
1977/8	-0.14	-0.35	-0.28	0.09	0.05	0.28	0.07	0.20	0.08
1978/9	-0.16	-0.38	-0.30	0.11	0.06	0.29	0.09	0.19	0.11
1979/80	-0.18	-0.39	-0.30	0.13	0.05	0.29	0.10	0.16	0.15
1980/1	-0.16	-0.38	-0.26	0.11	0.04	0.30	0.07	0.15	0.10
1981/2	-0.17	-0.38	-0.32	0.11	0.07	0.28	0.10	0.20	0.13
1982/3	-0.12	-0.32	-0.26	0.07	0.05	0.28	0.05	0.21	0.06
a	-0.083	-0.264	0.21	0.078	0.006	0.28	0.013	-0.14	-0.054

a = average of twenty estimates

(Appendix III.8 Continued)

2. PARTIAL ELASTICITIES OF SUBSTITUTION; COMPLETE MODEL

	A_{KK}	A_{LL}	A_{FF}	A_{KL}	A_{KF}	A_{LF}
1963/4	0.02	0.35	16.2	0.15	-0.65	-3.01
1964/5	0.02	-0.29	18.2	0.21	-0.72	-2.85
1965/6	0.02	-0.23	24.7	0.20	-0.90	-3.32
1966/7	0.01	-0.75	19.3	0.26	-0.77	-2.64
1967/8	0.01	-0.75	18.2	0.25	-0.74	-2.57
1968/9	-0.02	-1.32	9.6	0.33	-0.48	-1.56
1969/70	-0.07	-1.76	5.05	0.45	-0.33	-0.67
1970/1	-0.09	-1.78	2.28	0.46	-0.17	-0.35
1971/2	-0.14	-1.73	0.67	0.52	-0.09	-0.01
1972/3	-0.14	-1.72	0.89	0.52	-0.12	-0.01
1973/4	-0.11	-1.77	1.51	0.49	-0.14	-0.18
1974/5	-0.12	-1.78	-0.41	0.44	0.07	-0.04
1975/6	-0.28	-1.56	-1.62	0.53	0.23	0.50
1976/7	-0.24	-1.67	-1.62	0.49	0.26	0.44
1977/8	-0.23	-1.74	-1.66	0.45	0.32	0.42
1978/9	-0.27	-1.67	-1.69	0.48	0.32	0.51
1979/80	-0.32	-1.53	-1.69	0.52	0.28	0.57
1980/1	-0.26	-1.65	-1.62	0.50	0.25	0.45
1981/2	-0.29	-1.64	-1.69	0.48	0.34	0.54
1982/3	-0.18	-1.78	-1.62	0.42	0.32	0.31
a	-0.134	-1.314	5.15	0.406	-0.14	-0.67

a = average of all twenty estimates

Notes to Chapter III

(1) Westoby and McGuire (1984) p.115.

(2) This information in various issues of the National Institute Economic Review and The Financial Times for the relevant period.

(3) See Chapter VI.

(4) Handbook of Electricity Supply Statistics 1984.

CHAPTER IV

INVESTMENT APPRAISAL AND INTERTEMPORAL PROBLEMS IN THE COST BENEFIT ANALYSIS OF NUCLEAR POWER

Nuclear power presents particular problems concerned with the economic analysis of time. This chapter analyses the various methods of investment appraisal and discusses whether public sector appraisals need to adjust the discount rate. It considers the debate over the possibility of using a zero (or negative) rate for nuclear power projects and the question of intergenerational equity which is raised by the irreversible nature of the consequences of developing nuclear power. The concept of option value is applied to the nuclear investment decision to give an indication of the direction of adjustment which would be required (when formulating costs in a SCBA) to accommodate intergenerational equity considerations.

IV.1 INVESTMENT APPRAISAL

IV.1.1 The Payback Method

The simplest decision criterion a company could use when considering an investment project is the payback criterion (PPC), which estimates the length of time the project will need to generate revenue sufficient to cover the original cash outlay. Thus, a project whose net revenues are -50, 10, 20, 20, 30, has a payback period of 3 years. For a given project the firm will compare the payback period with some maximum, and reject it if it exceeds this maximum. If a set of alternative projects is being considered, the PPC ranks them by giving the highest position to the project with the shortest payback period, (and so on).

Bierman and Smidt (1980) note that this is "apparently one of the most frequently used methods of measuring the economic value of an investment" (1), and that "investigators have reported that maximum payback periods of two, three, four or five years are frequently used by industrial concerns" (2). The brevity and variability of these maxima implies that different types of investment will be put into different maximum classes.

Clearly, this is a very simple criterion, ("an extremely crude rule of thumb" (3)), but its frequency of use implies some advantages. De la Mare (1982) notes two: that the imprecision and unreliability of general forecasting techniques gives the PPC a measure of certainty and desirability; and that the PPC is actually a criterion concerned with company liquidity (rather than economic efficiency), and companies are often critically constrained by cash flow.

Nevertheless, the PPC has no satisfactory economic justification, and these two supposed advantages do not stand any rigorous test. The first 'advantage' represents a way of dealing with risk in future estimates - but the PPC does this by the extreme method of ignoring any risk up to its maximum point. Similarly, it deals with time preference by promoting projects with the shortest payback period.

Second, liquidity may certainly be a constraint, but easing it through the PPC will lead a company to reject profitable projects which fail to meet the short-term stringency of the criterion. Furthermore, when comparing two projects, the PPC always picks the one paying back first, even through another may pay back substantially more after an early delay.

In general, the PPC fails to analyse the economic merits of investment projects, and ignores completely anything connected with the project after the maximum payback period. Alternative procedures (reviewed below) will look at net benefits beyond that point and, clearly, may give very different results. Sugden and Williams (1978) state that the PPC is only justified by the assumptions (i) that shareholders have marginal time preference rates of zero; and (ii) that projects have neither returns nor costs after the maximum payback point. The latter assumption is likely to be generally violated, which requires a more sophisticated criterion to be used.

The next step would be to use the Discounted Payback Criterion (DPC). Here, the rule is to estimate the time period required before the present value of the project switches from being negative to being positive - what is being estimated is the breakeven life of the project. (A project having an economic life greater than the estimated breakeven life has a positive net present value). This step deals with the criticism of the PPC that it ignores the "time value of money" - but the other criticisms still hold, since the arbitrary nature of the maximum payback period has no economic justification. Thus, despite its widespread use, a payback criterion is not acceptable in investment appraisal.

IV.1.2 The Net Present Value Method

If it is assumed that the company's future stream of benefits and costs arising from a given investment project lasting n years have been estimated, then the present value of that project is given as

$$NPV = (B_o - C_o) + \frac{(B_1 - C_1)}{(1 + R)} + \frac{(B_2 - C_2)}{(1 + R)^2} + \ldots + \frac{(B_n - C_n)}{(1 + R)^n}$$

And projects whose NPV > 0 should be undertaken.
Since the B and C values are assumed known, the remaining problem is the value of the interest rate R in the discounting factor $1/(1+R)^t$ $t= 1,\ldots,n$. Here the firm may use a straightforward opportunity cost argument. Assume it has sufficient funds (perhaps undistributed profit) to undertake the initial project expenditure. The opportunity cost of the project is what those funds could earn elsewhere - and since they could be invested in "the" money market, then the interest rate obtaining there measures the opportunity cost.

Here, assume for simplicity that there is a perfect capital market so that there is just one borrowing and lending rate for the firm to consider. The practical and theoretical difficulties of a less than perfect market are important elements later.

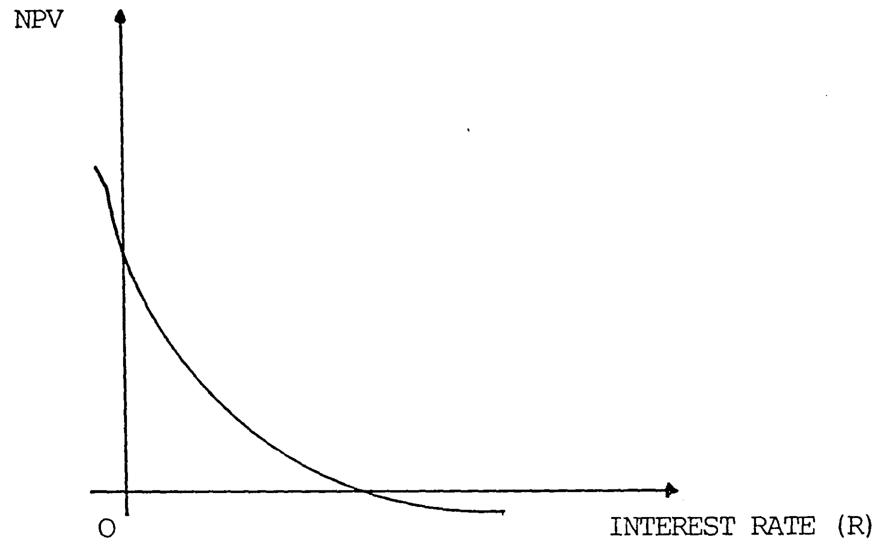
Alternatively, the firm may be assumed to have no available funds and so must borrow to finance the project. Again in this case, the opportunity cost of the funds is measured directly by the money market interest rate.

Now the B, C and R values are known (if R is predicted to vary over the life of the project all that is required is that its different estimated values be used in each year), and the value of NPV can be calculated. The investment rule is simple: if NPV > 0 the project should be undertaken. Since R is the opportunity cost of the funds devoted to the project the positive NPV is telling the firm that this piece of investment will yield a return in excess of either what could have been earned in the next best alternative use - the money market, or what borrowing the initial outlay will cost in interest payments.

Clearly the value actually taken by R is highly significant in determining the size of the NPV and for a given stream of net benefits the relationship will be as in Figure IV.1.

Figure IV.1

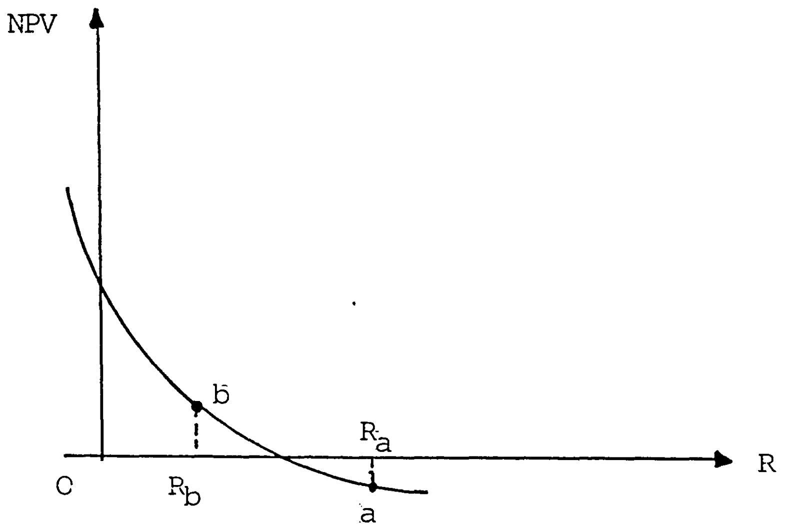
<u>NPV/Interest Rate Relationship</u>



Further influences from different values of R should be noted. If a set of projects has been evaluated at a particular rate of interest and some rejected then lowering the value of R sufficiently will cause some of those previously rejected to become acceptable. In Figure IV.2 a project can be moved from a to b by reducing 'R' in the discount factor from Ra to Rb.

Figure IV.2

Changing the Discount Factor



In addition a "low" value of R (by which is meant low historically or in comparison with current interest rates), will have an effect on the type of project that is undertaken. Projects whose net benefits become positive comparatively far in the future suffer from the effect of a bigger discounting factor being applied to those net benefits. As R is made lower, so is the effect of $1/(1+R)^t$, and such projects can be made worthwhile. Typically these will be durable investments with a succession of negative net benefits as (substantial) capital expenditure is undertaken for the early years. Hence "low" values of R will tend to encourage capital intensive, durable projects yielding the majority of their positive net returns later in their lives. This implies that using low values for R may not be the best way of encouraging rapid expansion in a recessed or developing economy.

IV.1.3 The Internal Rate of Return Method

An alternative approach to the problem of investment appraisal would be the internal rate of return method. Consider the NPV equation:

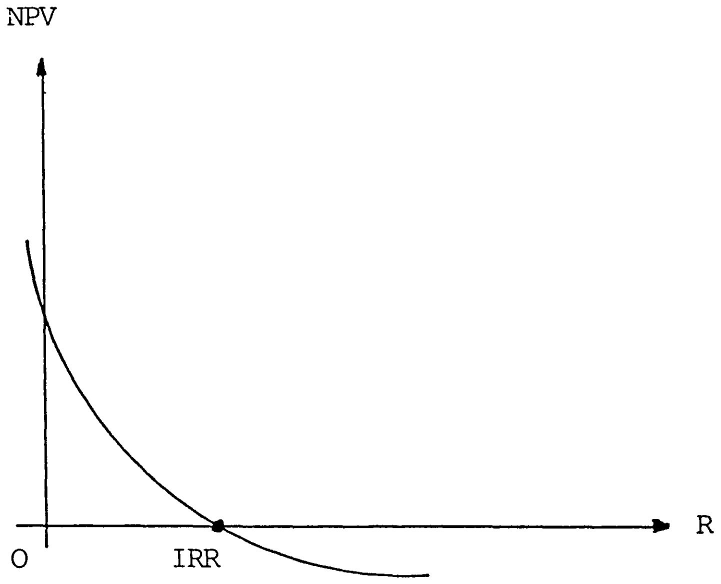
$$NPV = (B_o-C_o) + \frac{(B_1-C_1)}{(1+i)} + \frac{(B_2-C_2)}{(1+i)^2} + \ldots + \frac{(B_n-C_n)}{(1+i)^n}$$

Now, set NPV = 0 and solve the polynomial equation for i.

This approach finds the rate of interest at which net benefits are zero, and that rate is known as the internal rate of return (IRR) on the project. The investment rule now becomes: compare the value of the IRR with the opportunity cost of the funds (the money market interest rate R). If i > R then the investment should be undertaken. In terms of Fig. IV.1, the IRR method is solving for the value of R at which the curve cuts the horizontal axis ... Figure IV.3.

Figure IV.3

Internal Rate of Return



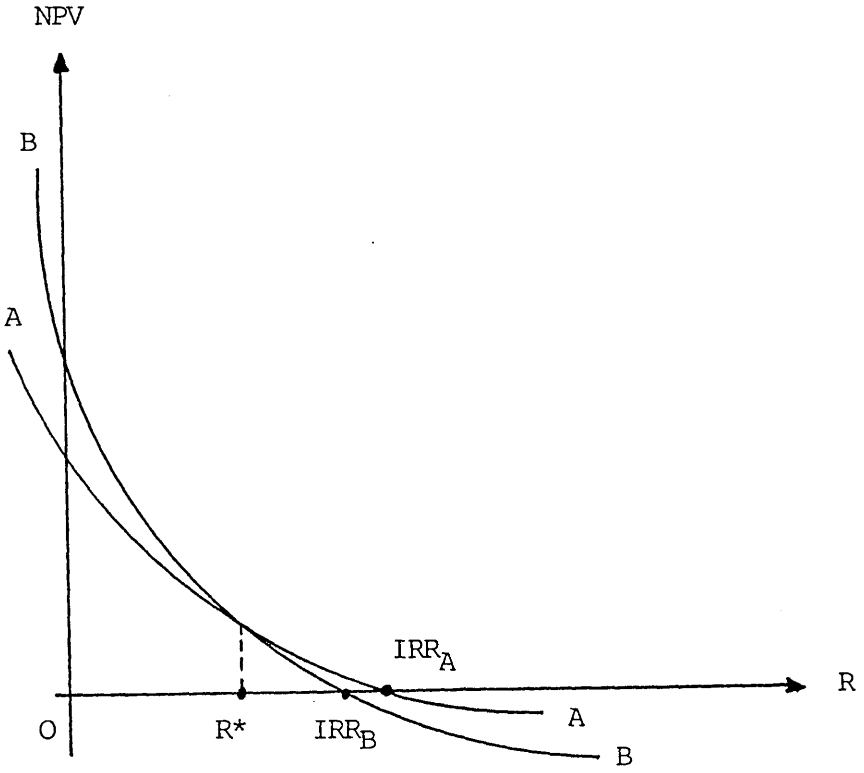
Intuitively the rules seem equivalent. A positive NPV implies the project is offering a return in excess of that available in the money market, and thus an internal rate of return greater than the money market rate should also be expected.

There are, however, difficulties with the IRR rule which render it inferior. The first is that solving a polynomial can yield several values for i; some will be imaginary numbers, some negative, but some will be - apparent - alternatives, with no means of choosing which one to consider.

Second, consider two mutually exclusive projects A and B, each with a given stream of net benefits. The NPVs are shown in Figure IV.4.

Figure IV.4

Mutually Exclusive Projects



The IRR rule always selects project A as it has the higher internal rate of return. At interest rates above R* the NPV rule also selects A; but should the opportunity cost interest rate be below R*, B becomes preferred, yet the IRR rule takes no account of this.

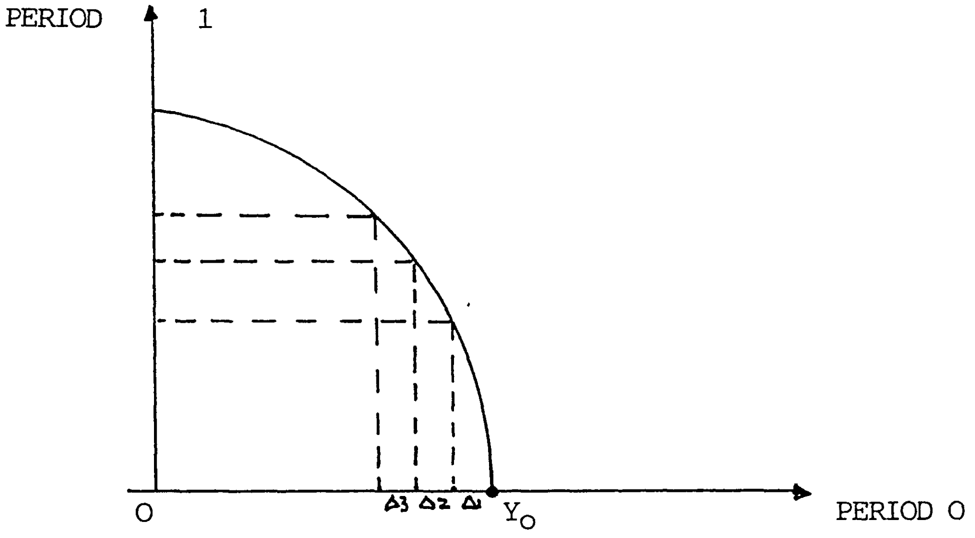
The third difficulty follows, in effect, from the second. The IRR rule tends to discriminate against projects having net benefits later in their life. Assume the NPV rule has shown two different projects to have equal, positive NPVs. Project A has positive net benefits early in its life, project B has a comparatively long series of costs, followed by positive net benefits. The IRR rule, however, will rank A as preferred to B; this is because the rule is solving for the value of i which sets the NPV equations for A and B equal to zero. The net benefits for B come late in its life, hence the discount factor applied to them to render them equal to those of A (at zero), will have to be lower than that applied to project A.

The NPV rule is thus superior, and should be adopted for appraisal of public sector investment projects.

A company's investment behaviour may be illustrated with the "Fisher Diagram". Assume only two periods, an interest rate R% (from a perfect capital market) and a company income of Y_o in period zero which may be consumed or invested in equal unit increments. Each unit of investment will produce a return next period and these are subject to the law of diminishing returns. This produces the investment opportunity locus of Figure IV.5.

Figure IV.5

Fisher Diagram



Equal incremental blocks of investment taken from Y_o yield successively decreasing returns in period 1. The slope of this locus is $-dY_1/dY_o$.

The firm also faces a market opportunity locus determined by R and the endowment Y_o. This could all be consumed in period O or all placed in the money market to yield $Y_o(1+R)$ in period 1, or some combination. This locus is shown in Figure IV.6, and has a slope of $-(1+R)$.

Figure IV.6

Market Opportunity Locus

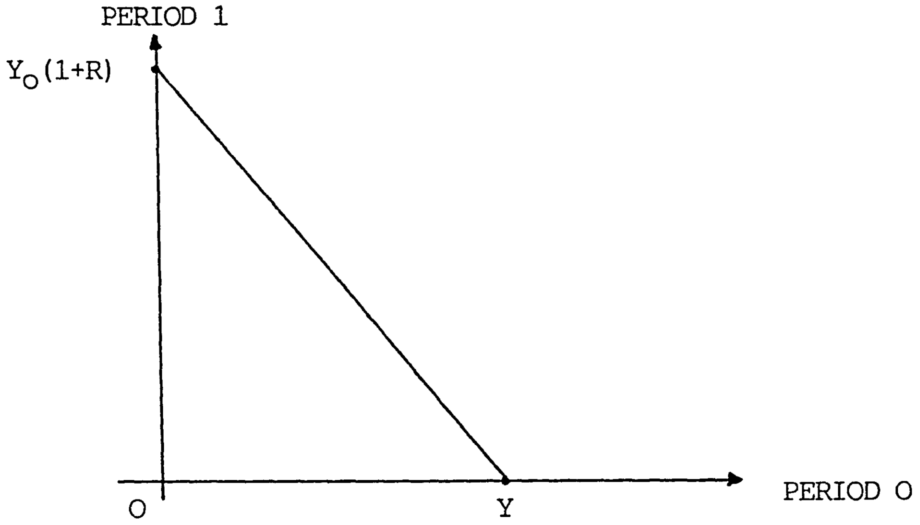
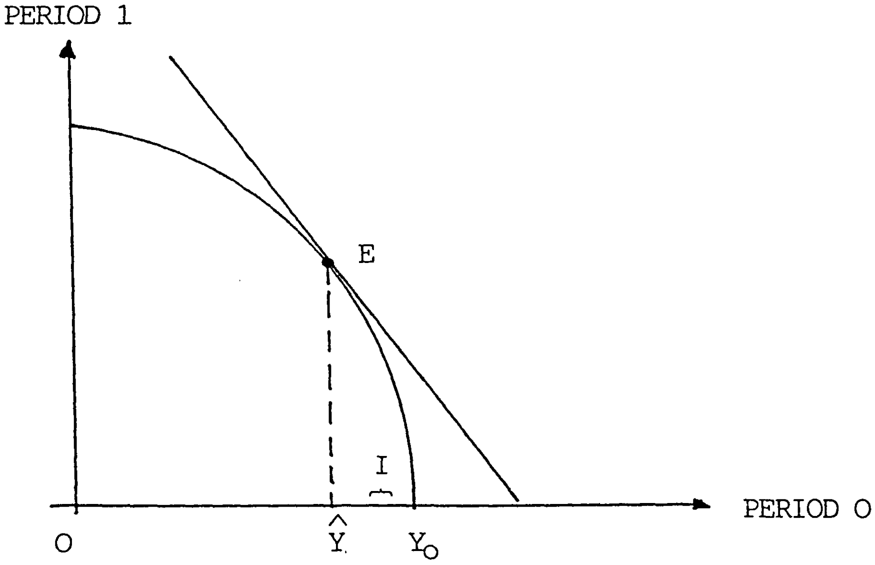


Figure IV.6 is now superimposed on Figure IV.5 to determine the optimal level of investment. The market opportunity locus is shifted rightward until just tangential to the investment opportunity locus ... point E on Figure IV.7.

Figure IV.7

Optimal Investment



At E the NPV of the last increment of investment has fallen to zero and investment should cease - the total sum having been invested is $Y_0 - \hat{Y}$. Note that at E

$$-dY_1/dY_0 = -(1 + R) \qquad \text{or} \qquad dY_0 = \frac{dY_1}{(1+R)}$$

the discounted value of the returns in the next period is exactly equal to the amount given up this period to earn those returns: at the margin the net present value is zero.

IV.2 THE DISCOUNT RATE IN THE PUBLIC SECTOR

IV.2.1 The Market Rate of Interest

Since the public sector in the UK undertakes a substantial proportion of the country's total annual investment, the choice of discount rate - now termed the social discount rate (SDR) as it is to reflect society's decisions on investment appraisal - is of great importance. Its value will determine both the type of capital projects chosen (see above), and the balance of the allocation of resources between public and private sectors.

Following the publication of Cmnd 7131 [1978] the Treasury has required nationalised industries to earn a real rate of return (RRR) of 5% on their new investment. This was intended to cover investment programmes as a whole rather than individual projects, hence some particularly "high earning" investment opportunities might subsidise others unable on their own to achieve a 5% return in real terms. The RRR was introduced to meet a set of objectives which includes a number of the claimants for the role of SDR, (and may thus be contradictory).

These are that the nationalised industries' discount rate should reflect the low risk returns available in private sector investment; that it should reflect the currently expected productivity of investment; and that it should correspond to the social time preference rate (4). The first two of these objectives are opportunity cost arguments, referred to by Baumol (1977) as the "basic criterion". Total investment funds in any period are taken to be an essentially fixed quantity, (fixed by an underlying assumption of high or 'full' employment). Thus any new piece of public investment will have to be at the expense of the marginal private investment, assumed now to be the marginal low-risk private investment, as government projects are all assumed low-risk. (This is discussed further, later). So, if that displaced piece of private investment could have produced a return of X%, then the alternative public use of the investment funds is only acceptable if it can return at least X%. Any other rate will cause an imbalance between private and public sector investment and so reduce social welfare.

The third objective involves an apparently more subjective criterion. Individuals clearly have intertemporal preferences and any individual's consumption and borrowing/saving behaviour will be partly determined by the shape of the indifference curves between present and future periods' consumption. Assume that each of the m individuals in society has a utility function defined over the consumption of n goods xl ... Xn:

$$U_i = U_i(Xl_i \ldots Xn_i), \qquad i = 1 \ldots m$$

and that $dU_i/dX_i^j > 0$. $\qquad j = 1 \ldots n$

From this it is conceptually possible to write an aggregate social welfare function W:

$$W = W(U_1 \ldots U_m)$$

where $dW/dU_i > 0$.

If such a function is assumed to have the same desirable properties as are usually assumed for individual utility functions, then a social indifference map may be drawn between two goods, just as is done for individual consumer analysis. The prodigious constraints on how far this may be taken are discussed in Dobb (1969).

Now, if it is acceptable to aggregate individual preferences into some overall index of "social welfare", then the individual time preference rates may also be aggregrated into an average which gives society's measure of the relative merits of consumption today and tomorrow.

Hirshleifer and Shapiro (1977) show that these two criteria can, under certain circumstances, be identical. If so, the targets set for the RRR are feasible theoretically even if still to be estimated in practice.

Hirshleifer and Shapiro divide the economy into two sectors: consumption and production. In the consumption sector time preference is a measure of the consumers' willingness to sacrifice consumption now for consumption in the future. It is the return required to make that sacrifice. If at the margin a consumer required £1.15 next period to compensate for the sacrifice of £1 now, then that consumer's marginal rate of time preference is 15%. Clearly the consumer will borrow (lend) current wealth in the market to adjust into equality the subjective rate of time preference with the market rate of interest. If the money market was offering 20%, the consumer would lend; but increasing the flow of funds would tend to reduce the interest rate until at the margin the two were equal.

In the production sector time productivity measures the objective ability of firms to invest today and earn a return in the form of increased future output. If a firm can invest £1 today (sacrifice current consumption), and obtain a yield of £1.18 next period, then the marginal rate of time productivity is 18%. Given the argument above it is clear that the firm will invest up to the point where its marginal time productivity is equal to the market rate of interest.

Thus both sectors react to the market rate of interest and by so doing cause it to adjust. With the money market conditions above the firm would curtail investment, and this reduction in demand for funds would give a further stimulus to the decline in the rate of interest. In equilibrium the money market will produce an interest rate which simultaneously mirrors the objective marginal time productivity of the production sector and the subjective marginal time preference of the consumption sector. With this result the Government could legitimately choose the market rate of interest to reflect the criteria of opportunity cost and of social time preference. The result is, however, far too reliant on (implicit) assumptions and omissions.

Feldstein (1964) has discussed the problems arising from the assumption of a perfect capital market which is required in the above theory. The most important of these is that every sector of the economy needs to act in accordance with perfect markets for the result to hold. This means that an individual's decisions on future behaviour will be based on the knowledge of the future behaviour of others, whose behaviour is in part determined by that of the original individual ... and so on. A firm's estimate of the time productivity of possible new capital depends on the volume of investment throughout the economy, which is partially influenced by whether or not that firm invests.

In practice capital markets are very far from perfect and also generate a large number of interrelated but different rates. Borrowing and lending rates are not equal and differ among market users. The work of Hirshleifer and Shapiro indicates that this outcome could, however, be useful in practice; while that of Arrow and Lind (1970) argues to the contrary.

Although Feldstein's objections are very powerful, there still remain (i) Baumol's proposition echoed in many cost benefit texts, that the basic criterion for government choice of social discount rate remains opportunity cost, and (ii) the proposition that government investment should reflect the relative dislike of the future compared to the present felt by society as a whole.

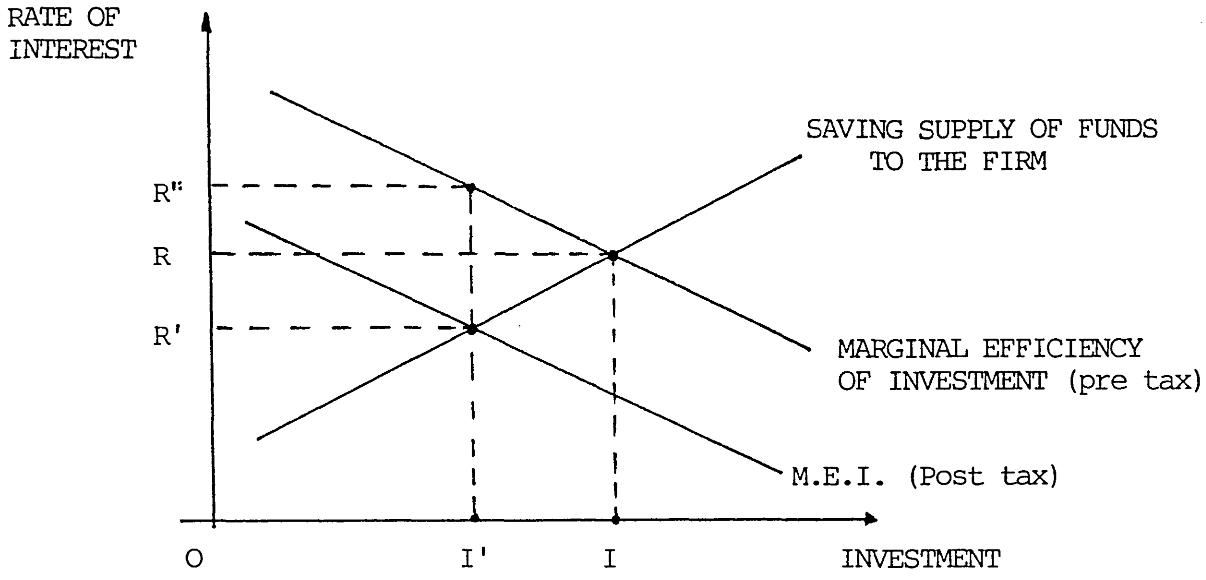
IV.2.2 Social Opportunity Cost

In the example above the marginal time productivity of capital in the private sector was reflected exactly in the perfect capital market rate. In practice there is a series of complications which mean that observed rates are not an immediately satisfactory guide.

First the measure of the opportunity cost of capital in the public sector is distorted by taxes on private sector firms.

Figure IV.8

Tax and the Opportunity Cost of Capital



In the absence of taxes the firm in Figure IV.8 should be observed earning a return of R% which would then be the opportunity cost relevant to the government. When faced with corporation tax the firm has to pay both shareholders and Inland Revenue from its profits/earnings and the marginal efficiency of investment schedule (MEI) will shift down. The level of investment falls to I' and the apparent opportunity cost to R'. In fact the relevant cost is the return before tax, R", which is what society is actually earning on investment of I'. The need to correct rates of return for tax payments is stressed in Baumol (1977), Arrow & Lind (1970), Pearce & Nash (1981). However Cmnd 7131 (1978) stresses that its RRR is a rate which has taken tax payments into account.

The second problem relates again to the imperfections or failure of the market mechanism. In Figure IV.8 it is essential that the investment schedule be derived taking into account all externalities relevant to the firm and to society. If the firm's investment project involved a waste output which increased the toxins in the river where it was dumped, but no account was taken of this in the investment appraisal, the resultant return shown on the project would be too high. The social opportunity cost should then be adjusted to accommodate the unpriced effects distorting the private sector's apparent returns.

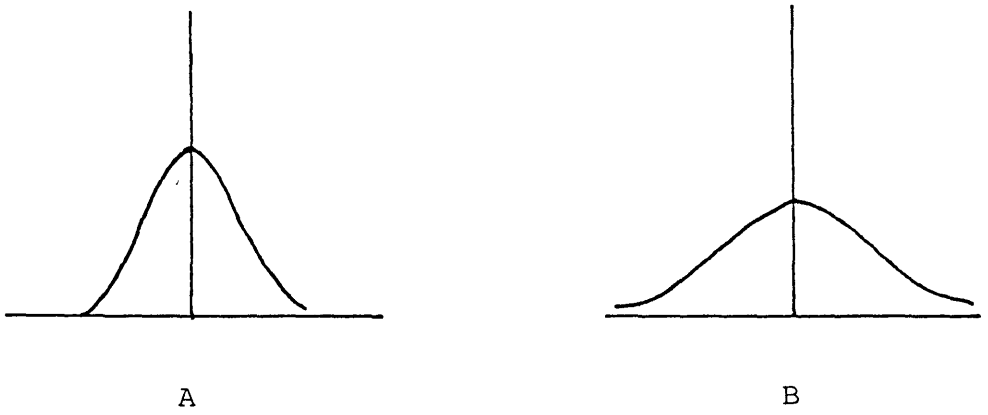
The third major area of contention relates to the relevance of risk to the public sector:

IV.2.3 Uncertainty, Risk and the Social Opportunity Cost

Risk and uncertainty are generally distinguished. Hence risk is characterised by a set of future alternatives to whose occurrence may be attached probabilities, whereas Keynes (1973) refers to uncertainty as "primarily characterised by a lack of confidence in probabilities high or low" (see also Weintraub (1975)). F H Knight (1971) also uses this distinction. Thus if two securities, A and B, had normal probability distributions of returns with the same expected value but different variances (Figure IV.9):

Figure IV.9

Riskiness of Securities



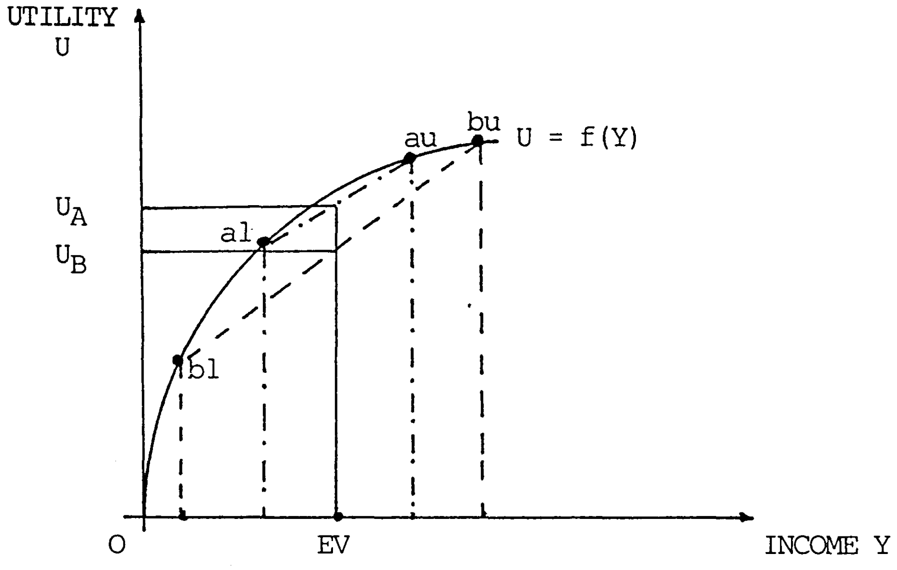
then security B would be regarded as riskier. Shackle (1974) takes the probability example further. He argues that the relative frequencies attached to risky outcomes may indeed be viewed as objective probabilities. Given a set of future events the sum of the probabilities of each will be one. When dealing with uncertainty we still attach probabilities to the various future events we may predict. However, in the latter case the probabilities are subjective; their sum need no longer be one and, indeed, if an extra event is added to the set the previous subjective estimate of each probability need not change. Risk and uncertainty in this tradition are clearly different things. The difference is dismissed by Hirshleifer and Shapiro (1977) who note the above approach but argue that rational intertemporal action always requires individuals to make use of their available information (however limited it may be), in the form of a probability distribution. In consequence the distinction may be ignored. Risk and uncertainty may be used interchangeably to refer to cases where a number of different outcomes can result.

In the context of nuclear power decisions it is not at all obvious that this conflation of the two terms is satisfactory and the analysis of an uncertain future as one which may involve events which simply cannot be predicted may be central in enabling the creation of a framework for decision making.

If the debate over this distinction is temporarily ignored, the significance of risk may be analysed. Figure IV.9 above might be viewed as the outcomes offered to prospective investors in two different firms; the expected values of the returns are the same but firm B is a riskier proposition. It is argued that to tempt investors to firm B a risk premium will have to be offered. This assumes that investors as a class are risk averse. Apart from a limited number of individuals, it seems that gambling occurs only when the variations in wealth involved are relatively small. That is, when there are risks which can carry large losses the utility function may be expected to show diminishing marginal utility of income - or risk aversion - which will remain as the assumption. Figure IV.10 takes the example of the two firms whose securities carry different risks. It shows the utility of income for a risk averse individual;

Figure IV.10

Risk Aversion and Risky Securities



EV is the expected value of each security - assumed to be the same. Points au and al are taken to be the maximum and minimum possible outcomes for security A; similarly bu and bl for security B. The utility associated with buying A is found on the chord joining au and al above EV and is Ua; that for security B is Ub. The individual will prefer the less risky alternative. Hence assets which offer uncertain returns will not be assessed by their expected values, (which are equal for A and B), but by the expected values adjusted for risk. Hence, A may offer 10% and B 15%.

Hirshleifer (1966) and Hirshleifer and Shapiro (1977) have generalised from this private case to argue that risk is also a social cost which implies that governments must formulate the social discount rate in a way which accommodates risk just as private individuals do. Their analysis uses state preference theory; they assume the simplest case of a certain present and a one period future which has two alternative states of the world. This leads to the 'present certainty equivalent' rule as the generalisation of the NPV rule: the government should act to maximise the net present values from all possible states of the world considered together. Hence, consider a project costing £1 and having returns £3 if state A and £0 if state B. The benefits (£3 or £0) and costs (£1) are claims to consumption and as such have prices. Let $P_o = 1$ and let $P_{1a} = 0.3$, $P_{1b} = 0.5$. The latter are the market equilibrium prices for contingent claims. The project has a present certainty equivalent value:

$$PCEV = -1 + 3.(0.3) + 0.(0.5) = -0.1$$

and should accordingly be rejected.

Now given certainty the (single) future price of claims on consumption is $P_1 = 1/(1+R)$ where R is the riskless rate of interest. In the certainty equivalent case $P_1 = P_{1a} + P_{1b}$ which in the example above gives:

$$P_1 = P_{1a} + P_{1b} = 0.3 + 0.5 = 1/(1 + R)$$

hence the riskless rate of interest is 25%.

Now assume that states A and B are equiprobable, and consider again the project $\left\{-1 \begin{matrix} 3\} \\ 0\} \end{matrix}\right.$. The expected value of the future returns is 1.5. and if the project is discounted at the riskless rate:

$$PV = -1 + 1.5/1.25 = +0.2$$

which means the project is accepted .... which contradicts the rejection above. Hence Hirshleifer and Shapiro conclude that in general a "risky" rate of interest should be used by the government (except in the case where the probabilities of outcomes of each state are proportional to the prices of claims to consumption in each state).

In addition they show that projects can be defined to be in particular "risk classes", and each risk class requires its own discount rate. Thus $\left\{-1 \;\; \begin{matrix}3\\0\end{matrix}\right\}$ would be in the same risk class as $\left\{-4 \;\; \begin{matrix}7\\0\end{matrix}\right\}$. The riskless class would be represented by a project such as $\left\{-1 \;\; \begin{matrix}3\\3\end{matrix}\right\}$.

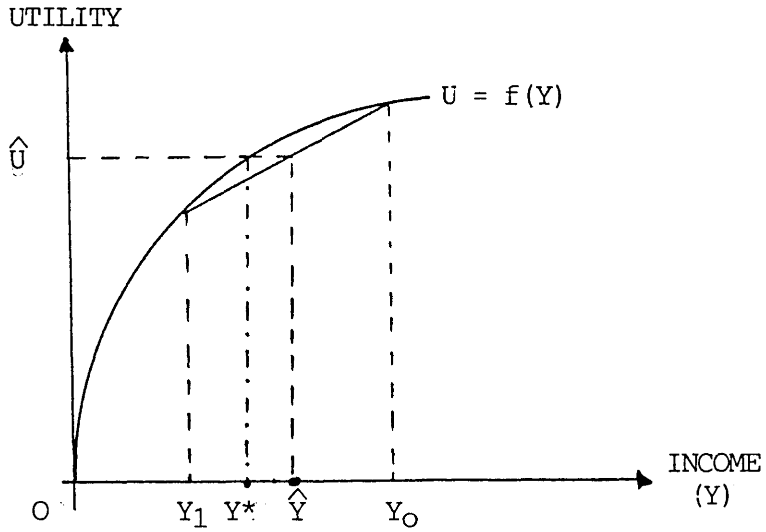
While this analysis has deliberately chosen the simplest possible model, it indicates that risk is a social cost and that governments should consider which private risk class is relevant for each of their potential projects. Thus projects A and B above with 10% and 15% returns may be representative of two such risk classes and thus provide the government with a guide to the discount rate it should use if it is contemplating comparable projects.

If the government fails to take risk into account then it will tend to overinvest - in the sense that some public sector investment will be at the expense of higher yielding private investments.

Arrow and Lind (1970) however, use the same state-preference approach to demonstrate that the government should act as an expected value decision maker in cases of uncertainty; that requires the government to ignore the uncertainty and discount projects with a rate which would be relevant for investments with certain outcomes. The only additional assumption they require is that any given project should have returns which are uncorrelated with (movements in) national income. This result is achieved due to the government's ability to pool risks by pooling investments. The government undertakes a large number of projects; if these were all to be considered as private sector investments they would fall into various risk classes. If all the necessary conditions hold for general equilibrium, there would be a complete set of future markets for contingent claims in the various possible future states of the world. In particular there would be perfect insurance markets and these would permit the private sector to pool the risks attached to different projects and generate a Pareto optimal outcome. Perfect risk pooling would equalise the expected returns from projects through the insurance and re-insurance markets. Of course such a set of markets does not (and could not) exist, so that neither the Hirshleifer and Shapiro nor the Arrow-Lind results, which are implicitly based on a model assuming these perfect insurance markets, apply. The specific drawbacks which limit the formation of insurance markets are noted by Arrow-Lind as moral-hazard (purchase of insurance alters the buyer's behaviour adversely for the insurer), and the transactions costs arising from the complexity of the necessary contracts. In Figure IV.11 an individual with income Y_o faces a 50% probability of a loss which would leave income at Y_1. The expected value of income is $\hat{Y}'$; a certain income of Y^* yields the same utility as that associated with the risky situation.

Figure IV.11

<u>Risk Aversion and Insurance</u>



This implies that the individual would be prepared to pay an insurance premium up to a maximum of Y_0-Y* rather than face the risk. Clearly if circumstances were so complex that no insurance company could provide a contract at the premium then the individual would prefer to take the risk. But this means that the capital market rate of interest does not reflect (at the margin) equal rates of time and risk preference across individuals. The imperfections of the capital markets that actually exist imply sub-optimal investment over the economy.

However, the Arrow-Lind argument in favour of the government using a social opportunity cost discount rate which ignores risk still holds. It cannot be based on the government's ability to pool investments - acting, in effect, as if perfect insurance market results obtained. Instead it is based on the proposition that as the government spreads the risk of a particular project over the whole population (or, at least, the whole population of taxpayers), the risk to each individual becomes negligible. Hence the government should still be required always to use the discount rate relevant to projects with certain outcomes. Thus Samuelson (1964) gives the example of the borrowing rates available to different corporations, arguing that as the corporation size increases it begins to pool more (independent) risks and hence offers a safer investment opportunity to the market. Large corporations borrow more cheaply and may be expected to use a lower discount rate for their investment appraisal than smaller corporations in the same business. As Vickrey (1964) notes, the risk associated with a public project is pooled and averaged over the entire population. This represents the limiting case of the example presented by Samuelson and is similarly argued by Baumol (1977): "while the risk involved in any individual investment project is apt to be substantial for the supplier of capital, it may be negligible from the point of view of society as a whole". As the number of projects being considered becomes greater then "from the viewpoint of society they become, as a whole, virtually riskless" (5). Thus, suppose society is made up of n identical individuals, each having a welfare function whose arguments are uncertain income Y and the share (s) of the income associated with a possible government project. The latter income is $\overline{G} + x$, where $\overline{G}$ is the expected return from the project and x is a random element having a mean of zero. Hence the individual's welfare function may be written:

$$W = E[U(Y + s\overline{G} + sx)] \qquad [IV.1]$$

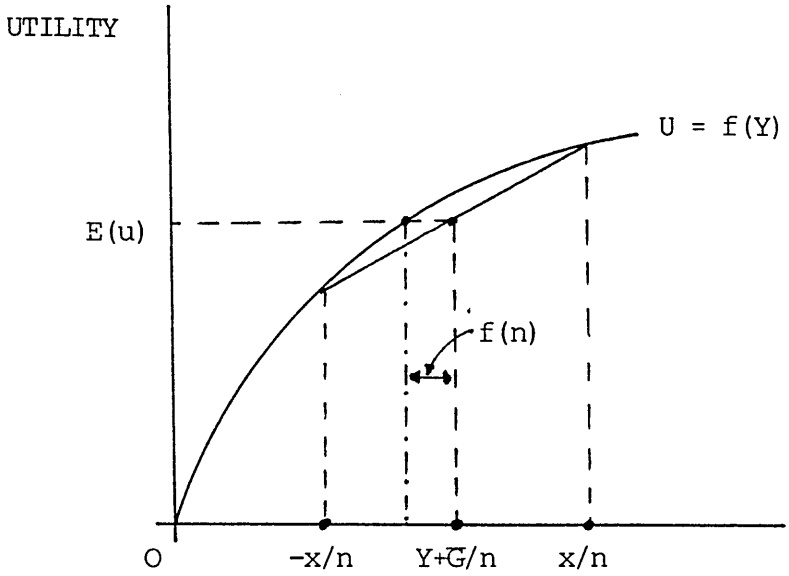
If all individuals share equally, then $s = 1/n$. Each individual is risk averse, which means, (as above Figure IV.11), that there can be defined a sum of money which the individual would be prepared to pay to avoid the risk involved with the project. In particular there will be a sum f(n) such that:

$$E[U(Y + \overline{G}/n + x/n)] = E[U(Y + \overline{G}/n - f(n))] \qquad [IV.2]$$

The individual would be indifferent between the risk involved in the project and paying f(n) to avoid that risk ... see Figure IV.12.

Figure IV.12

Risk Aversion and Payment for Certainty



Now, as $n \to \infty$ then Arrow-Lind note that lim $(n \to \infty)$ f(n) = 0; they then prove that lim $(n \to \infty)$ n.f(n) = 0. It is the latter proof that is important, as it means that provided n is large enough the project appraisal should consider only $\overline{G}$, the expected value of returns. This result holds despite the risk aversion which has been assumed for each individual and hence of society as a whole.

Pearce and Nash (1981) make two important points about this result. First they ask how large n needs to be in practice, for it to be considered sufficiently near to infinity for the Arrow-Lind result to hold. This is the point raised by McKean and Moore (1972): "80 million taxpayers is a long way from infinity and we are doubtful that the number is large enough to enable the US to get very much for nothing" (6).

Arrow-Lind (1972) themselves have noted the following requirements:

(i) the project cost should be small compared to the wealth of those paying for it. The U.K. has over 20 million income taxpayers (6) so that even projects which appear enormous against other investments will still be relatively small.

(ii) the share that each taxpayer must meet must be insignificant measured against the taxpayer's income. If this is so then it follows that the individual's cost of risk bearing is trivial and therefore the aggregate of all such costs is also negligible.

Pearce and Nash's second point is that the Arrow-Lind theorem relates entirely to the financial costs of the project. In effect, there are two parts to this argument. One, recognised by Arrow-Lind, is that should the risk of the project fall disproportionately heavily on a group of private taxpayers, then the time and risk preference rates appropriate to that group should be used for discounting, rather than the riskless rate proposed above. Two, there may well be costs which are neither explicitly financial, nor evenly spread across all taxpayers. The external effect of environmental degradation is a case in point and is considered by Fisher (1973). He shows that in such an example - particularly where the externalities are cumulative and/or irreversible - the risk to which a given group is exposed must be accounted for. To do this an extra sum must be added to the project costs to cover possible compensation to the group. This represents an attempt to internalise the externality by spreading the risk to society as a whole, and will involve transactions costs. The latter may be so large that the attempt to spread risk is prohibited - in which case Fisher recommends that the project's cost figures be increased to reflect the specific group risk.

Thus Fisher (1973) has detailed a particular example where the Arrow-Lind theorem no longer obtains. His examples are of "public bads" such as air pollution (where one person's consumption of the pollution has a negligible effect on the amount left to be consumed by others), or of environmental degradation or change which may be deemed irreversible. Fisher notes that the internalisation of such a risk is theoretically quite feasible through private insurance markets. But a central point of the Arrow-Lind work is that such markets do not exist. Hence, Fisher proposes that perhaps the government can intervene to cause the same result that the hypothetical insurance markets would achieve. The essential point here is that doing so involves adjusting the discount rate the government is using. (This is discussed further in the section on irreversibility).

Hirshleifer and Shapiro's (1977) view of the Arrow-Lind result (and of the closely associated arguments of Samuelson and Vickrey (1964)) is that it depends on market failure. Because insurance markets do not exist, or work only with exceptionally and perhaps prohibitively high transactions costs, some "high" return private sector projects are not undertaken and their place in the overall block of annual investment is taken by lower yielding public projects. In this view, the first best solution is not attainable in the market, but the second best of increased public sector investment should not be followed. Instead the first best is for the government somehow to subsidise the excluded private projects. Arrow-Lind reject this. The central point of their theorem is that by pooling risk over the population the cost of risk bearing (virtually) disappears; in that case "a public project with an expected return below that of a given private project may nevertheless be preferable" (7).

Hirshleifer and Shapiro also consider a second reason why the Arrow-Lind theorem may not hold. To derive the theorem Arrow-Lind assume that the risks attached to each project are independent or where projects are interdependent they should be amalgamated and treated as one independent set. Hirshleifer and Shapiro argue that it is quite possible for the expected/actual returns from government projects to be heavily influenced by the business cycle, which is a "social risk". If so the fact that the government is pooling many projects and spreading the risks over a large population no longer reduces those risks arising from the cyclical effects of (some) government projects. Similarly Haveman (1977) states that "even the proponents of this proposition ... recognise [that even if there is a relationship between the variability in the outcome and the variability in the performance of the economy] the pooling argument breaks down" and: "In spite of the Arrow-Lind theorem, numerous economists consider that social risk aversion is relevant in evaluating uncertain activities". (8)

Arrow-Lind dismiss these criticisms by assuming (i) full employment (as is, they claim, the case for most cost-benefit studies; this assumption permits the use of market prices in project evaluation)

(ii) that stabilisation policies are effective

(iii) that the Hirshleifer and Shapiro argument, even if correct, would be of little practical impact.

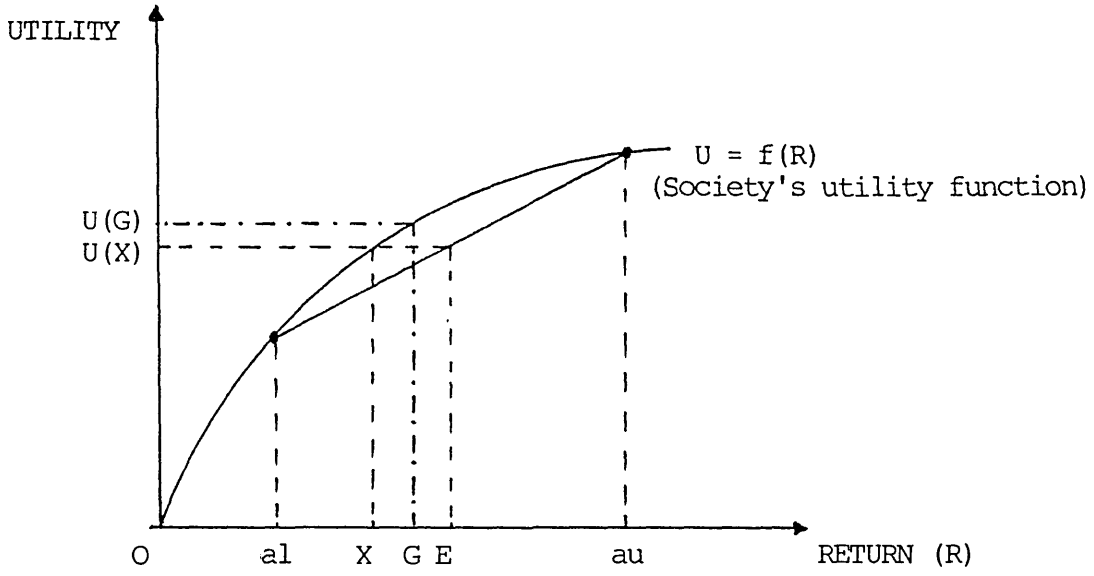
Despite this, Sandmo (1972) contrasts the arguments of Hirshleifer (as in Hirshleifer (1964) and (1966)) and Arrow-Lind, and asks if they can be reconciled. His conclusion is that such reconciliation is unnecessary because "the arguments are based on entirely different assumptions concerning the relationship between private and public investment with respect to risk". (9). He claims that the Arrow-Lind result depends on an assumption that the returns on private and public investment are uncorrelated, whereas Hirshleifer's result occurs because public investment projects can always be fitted into a particular class of private industry projects with which they are highly correlated. Sandmo's model shows that "the public sector's discount rates should always contain a risk margin" (10), and he argues that in a mixed economy private and public production are often undertaken side by side in some industries, lending weight to the Hirshleifer assumption.

While Sandmo does not argue that the Arrow-Lind result is 'wrong' - merely a different solution emanating from different assumptions - his insistence that his model considers social risks (which are due to the nature of technology and not removable by changes in the economy's social organisation), does seem to ignore Arrow and Lind's arguments noted above.

Figure IV.13 summarises the basic point of the Arrow-Lind theorem. A risky private project has upper and lower bounds for its returns of au and al and an expected return of E. But perfect insurance markets do not exist and a risk premium must be subtracted. This reduces the project's returns to a certain X. Society is, then, indifferent between a risky expected return of E, and a certain return of X.

Figure IV.13

The Arrow-Lind Theorem



An alternative government project yields G; this has its risk reduced to zero by pooling, so G is a certain return. Since G > X the government project should displace the private project even though G < E.

The cases where risk in public projects should be noted and lead to adjustments in the SDR are: (i) where irreversible environmental changes are associated,

(ii) where a particular group of individuals suffers risks which are not purely financial and which are specific to them. In this case a rate lower than the certainty rate should be used to discount these risks.

IV.2.4 Social Time Preference Rate

Above, it was argued that a perfect capital market would lead to the equalisation of the time productivity of the production sector and the time preference of the consumption sector. Since actual capital markets are not perfect, that equalisation is not achieved and the STPR remains a candidate for the SDR as an alternative to the SOC.

In a perfect world the equivalence of time productivity, time preference and the market rate of interest can be shown by adding to Figure IV.9 a social indifference map showing society's preferences between present and future consumption.

Figure IV.14

Time Preference

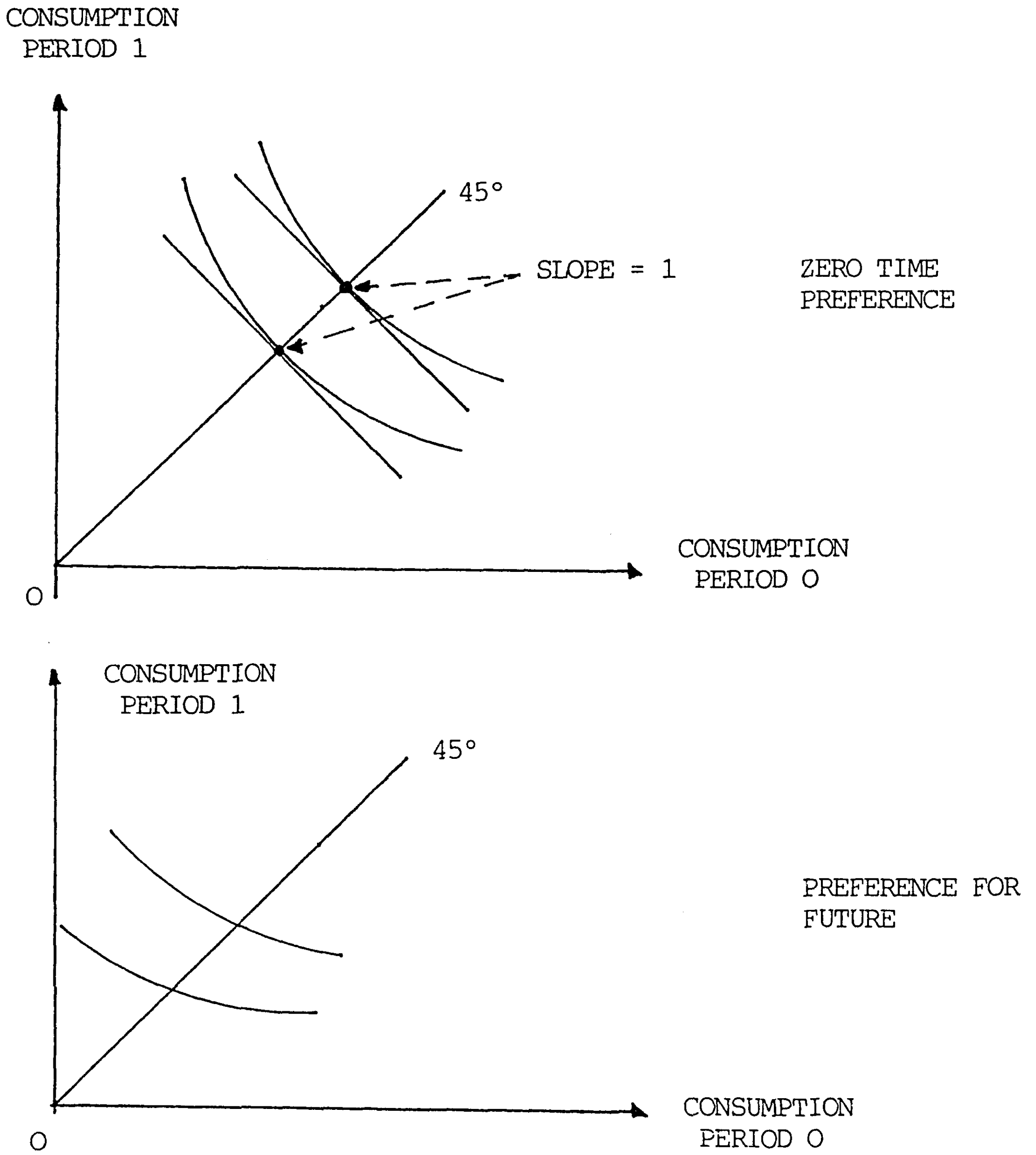
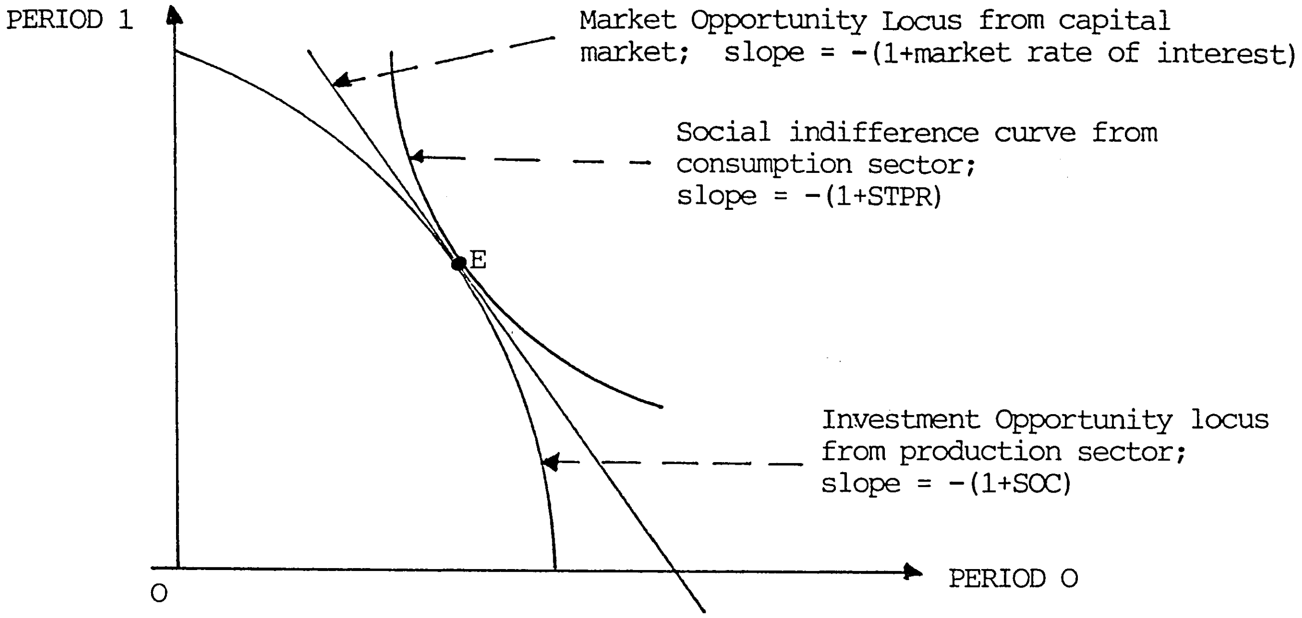


Figure IV.15

Socially Optimal Investment



At E on Figure IV.15 the rate at which society is able to transform current into future consumption equals the rate at which it wishes to do so; and both rates are captured by the market rate of interest.

The imperfections of markets, (and the private risk in investment), mean that such a result cannot be expected. In addition there are major problems associated with any attempt to estimate a STPR.

The first of these problems is due to the different time preference rates associated with individuals of different age groups. Presumably as individuals get older they begin to alter their preferences more strongly toward the present; if so a social time preference rate must be some average of these various rates. That leads to the question of whether this should be a simple average or whether differential weights should be attached to give the feelings of some groups relatively greater importance. The issue is further complicated by the suggestion that to be theoretically satisfactory the STPR must

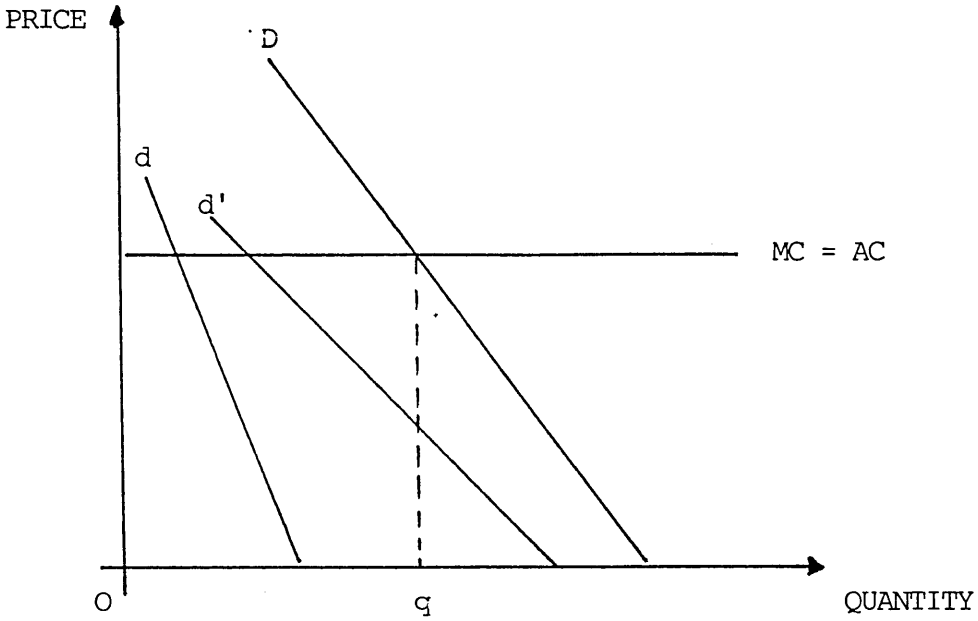
include in its averaging procedure the preferences of all individuals who will be affected over the entire lifetime of the project. But this will generally include people who are either still too young to vote or not yet even born. Their preferences are theoretically relevant (since the effects of the project will be part of their lives), but clearly immeasurable.
(This is discussed further under 'intergenerational equity')

If the latter problem is ignored, and if the imperfections of the capital market are viewed as minimal, then the latter's rate of interest should be giving some indication of society's saving behaviour and thus of its time preference. However, Sen (1967) has noted a further drawback which precludes using this (imperfect) relationship. In his analysis Sen generalises on the prisoner's dilemma from game theory to demonstrate what has since been termed the "schizophrenic' behaviour of individuals in the context of public sector investment, (11). Essentially, Sen presents the latter as a "public good" with all the associated problems of preference revelation for such a good.

In Figure IV.16 suppose that a particular public good (perhaps street lighting), can be provided at constant cost and that all but one individual have declared their true preferences for the good, so producing demand curve D

Figure IV.16

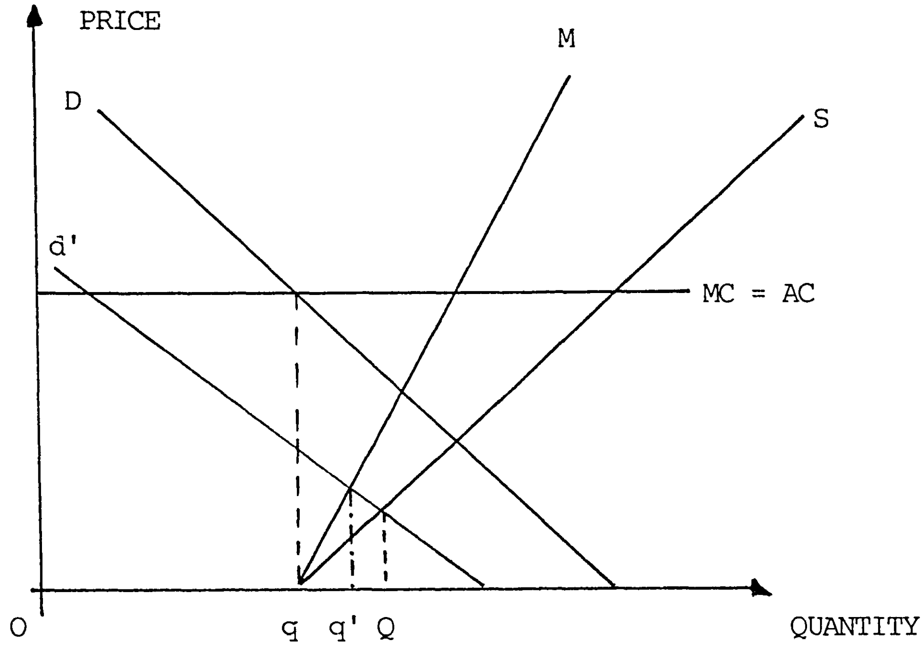
Public Good Demands



If the remaining individual had demand curve d (s)he would optimally declare zero preference for the good which would be available for (her)his consumption in quantity q paid for by the rest of society. If the remaining individual had demand curve d' then some preference revelation is indicated. By doing so the individual is shifting demand curve D upward - adding d' to it vertically. The cost to the individual of so doing is thus equal to the vertical distance between D and AC; Figure IV.17:

Figure IV.17

Public Good Demand and Supply for One Individual



Hence there is a supply curve of the public good to this individual (represented by S). But this is the average cost to the individual of revealing a preference and (s)he will act on the marginal curve M (which must lie above S) and so declare a willingness to pay, which results in society producing q' of the good. The optimal result is Q. In this example all individuals but one have declared their true preferences - and the one still makes a sub-optimal declaration. In practice demand curve D would not be known and some means would have to be devised to derive it. This is in essence what lies behind Sen's analysis.

Sen assumes two possible courses of action: A and B. B is the act of saving to provide for future generation(s), A is not doing so. In the most extreme case the assumptions on individuals are: (i) no matter what others do any individual is better off doing A than B (ii) everyone doing B is preferred to everyone doing A.

These two assumptions lead directly to a contradictory result: everyone will do A (assumption (i)), but would prefer that everyone did B (assumption (ii)). Given the meaning of A and B this inconsistent result makes sense; the optimal result of everyone doing B could only be achieved by some form of direct enforcement, since any individual will always attempt to do A, even if the rest of society was doing B. Sen refers to this as the "isolation paradox". The assumptions leading to this result are very strong, but imply that although the overall preference of society is for investment, each individual will choose to consume now. As a result the saving/ investment level is too low. If the market rate of interest was being used to represent the STPR then too little investment will occur as this rate is higher than society "wants" - but is unable to generate.

Sen then relaxes the first assumption on preferences into:

(i') if everyone else does B then the individual prefers to do B.

This leads to what he terms the "assurance problem". If the representative individual can be assured that all others will do B then that individual will also do B. The Pareto optimal result follows (12).

The implication of this analysis for a government attempting to derive a SDR is that the individual's declaration of preference for public investment will differ according to the behaviour of the rest of society. The investment is (partially) for the good of future generations. If all individuals are to forego current consumption so will the representative; if (s)he does not know the behaviour of the others then a personal sacrifice will not take place. By solving the assurance problem the state will be provided with the funds for increased investment; by merely taking the current market rate of interest as indicative of the STPR the government will be using a discount rate that overstates society's true social time preference. Hence the use of the term "schizophrenic": acting together society produces one rate; separately individuals generate another, higher rate.

The indication is that the private market rate of interest should be adjusted downward to produce the discount rate applicable to government projects. This is reinforced by the effects of a perfectly rational view of the future by individuals: each generation is richer than its predecessor. Given declining marginal utility of income (13), the future consumption benefits created by today's sacrifice will be given a value by future generations below what equivalent benefits would be valued at today. This gives a further incentive to spend rather than save today, and so leads to a higher market rate of interest.

Finally, individuals die, and fear of death promotes current consumption and an unwillingness to save for the good of unborn generations, (other than those immediately related to the representative individual). Society, of course, does not die, and must guarantee that its social investment is adequate to provide for future generations independently of the fear, avarice and unsocial behaviour of its present members. All these arguments imply a SDR below the market rate.

Warr and Wright (1981) argue that while the "isolation paradox" analysis is correct, it does not follow that public sector discount rates should be adjusted. They believe that this is a partial equilibrium result and their model runs over (at least) three generations to produce the conclusion that the market rate of interest should be used. Underlying their result is the ability of individuals to adjust their donations to future generations in the light of their view of the public project, and so smooth the latter's impact. An adversely affected individual (or generation) reduces the voluntary donation to the succeeding individual (or generation) and restores the equilibrium disturbed by the project, (and vice versa). However, Warr and Wright do note that "if the isolation paradox holds, the equilibrium under private savings is not Pareto optimal" (14). They go on to argue that adjusting the public sector discount rate is not a means of achieving a welfare gain - but presumably using it must sustain the sub-optimality despite the result of their general equilibrium model.

Mishan (1982a) presents a fundamental critique of the concept of a STPR. "Whenever inter-generation comparisons are involved ... it is as well to recognise that there is no satisfactory way of determining social worth at different points of time" (15). His argument is based on the immeasurability of utility which also led to Pareto's definition of how to distinguish welfare improvements for society. Since it is impossible to know the utility an individual in a future generation may derive from the effects of a project initiated now, present generations "have no business in evaluating the future worth ... by discounting" (16). Similarly, in Pearce (1976): "trade offs are all too easy to make when the gain is ours and the cost someone else's" (17).

This position has the danger of becoming very restrictive indeed and although Mishan notes the possibility of "potential potential Pareto improvements" (income redistributions at each generation), a strict interpretation of this view could lead to another "empty box" in welfare economics, prohibiting medium to long term investment.

A solution is proposed by Freeman (1977) using the Kaldor-Hicks compensation criterion. He notes that a large absolute sum representing costs long into the future is rendered trivial by discounting. Thus if such a trivial sum were invested at the beginning of the project, it would grow to be equal to those estimated costs and be available for potential compensation; "discounting works both ways" (18). Hence the CEGB (1984/5): "The Board is unique in the magnitude of the provisions it makes for expenditure to be incurred many years ahead. In 1984/5 £192m was provided to meet future expenditure on the decommissioning of nuclear facilities and the long term reprocessing of irradiated nuclear fuel and the treatment, storage and disposal of the resulting waste products. A further £30m was set aside for self insurance ... the accumulated long term provisions now stand at £1305m" (19).

Pearce (1977) argues that Freeman's proposition is a two-edged sword. It has the benefit that should a project have potentially infinite future costs ("social collapse or nuclear holocaust"), then the project would necessarily be dismissed. If, however, costs are finite, only a comparatively small sum would need to be invested now - and that makes "concern for the future a relatively unimportant aspect of decision-making" (20).

IV.2.5 Political Discount Rate

Since the amount of the adjustment suggested above is both crucial and not indicated by the analysis, it will inevitably have some arbitrary element. This is avoided in the suggestions from both Feldstein (1964) and Eckstein (1958 and 1970) who propose an explicitly normative, politically determined rate, (PDR).

The PDR is suggested because of two shortcomings of the market. First the market is imperfect and so fails to give any useful information about society's time and risk preference. Second, even if it is argued that the latter point is wrong as capital market imperfections are minor, nevertheless market information is still not what the government requires, as it reflects the current distribution of income and wealth and so gives higher weights to specific groups in the process of averaging individual time and risk preferences. There is no reason why the government acting on behalf of (at least) all current voters should wish to accept the particular bias in those weights.

Eckstein argues for a SDR lower than the market rate on these grounds, especially since the approach takes the state to have responsibilities deeper than merely some average of (some of) the individuals currently within it. The approach has the possible merit that unpopular decisions diminish the re-election chances of the government. However, the question of using politically determined weights is assessed (and rejected) in Chapter VI.

IV.3 NUCLEAR POWER AND THE SOCIAL DISCOUNT RATE

The Arrow-Lind theorem suggests that a project such as one or a series of nuclear power stations should be appraised using a SDR equal to that which would be used on marginal private sector projects with certain returns. The absolute size of the undertaking is immaterial as it is small in comparison with GDP. The clear risk which would surround any such private undertaking is pooled and rendered negligible.

This is the position taken by the CEGB in its calculations for the Sizewell 'B' Inquiry (21). "In Britain the government specifies financial guidelines for the nationalised industries which in general are required to make a 5% real rate of return on their investments, that is to say after allowing for the effects of inflation. This is interpreted as a requirement to appraise alternative power station projects using a 5% discount rate, provided that the appraisal separately deals with risk and uncertainty" (22). The reference to "separately dealing with risk and uncertainty" refers to the CEGB's attempts to make useful analysis based on forecasts over the next 30 or 40 years. The method chosen to do this is to adopt a set of "scenarios" - such as 'high', 'low' and zero growth of the demand for electricity - and undertake the investment appraisal within each of these scenarios.

Thus the CEGB approach follows the Treasury guidelines which as MacKerron (1982) (above) notes, require the public sector discount rate to reflect both opportunity cost and social time preference.

Jeffery (1983) and Pearce (1979) have both produced arguments that discounting as undertaken by the CEGB is inappropriate in the case of nuclear power. Both are concerned with the high costs that problems such as radioactive waste disposal may impose on future generations. Pearce gives as an example the following:

> Assume a monetary cost associated with radioactive waste in 50 years of £100 million, with a probability of 0.1. The expected value to that generation is £10 million. If the discount rate was 10% the discount factor in year 50 is 0.009 and the present value of the cost is £90,000. Pearce writes that "the conventional cost benefit analysis can make the nuclear waste disposal problem vanish by analysis" (23).

Jeffery is similarly concerned with the effects of discounting on the future costs associated with nuclear power - in particular those of dealing with radioactive waste and of decommissioning reactors. He argues that nuclear power is unique as these obvious costs will affect generations for periods long after the benefits of the reactors have ceased. Following Pearce's example, the CEGB/Treasury appraisal approach will render such costs as very minor items on the SCBA, yet they will represent major and continuing costs to the societies of the future. In effect the approach has a bias in it which naturally prefers projects with costs delayed long into the future; given two projects with the same total benefits and costs, it is the one having its costs pushed far into the future that this approach will always pick as superior.

Jeffery's argument that nuclear power is unique is based on its inevitable costs arising far into the future. The discussion of NPV rules almost invariably deals with projects whose costs arise immediately with benefits lagging. Jeffery's view of the RRR is that it is merely a means of ranking projects whose benefits occur at different times in the future, by progressively penalising those whose benefits are "far" ahead; the cost aspect may be ignored as arising early in all cases. (Arrow and Lind in their discussion of cases where the riskless SDR may need to be adjusted also note that in "most cases" costs are borne publicly and may be discounted at the certainty rate).

Pearce goes further in that (as in Kneese (1977)), he denies that SCBA is applicable at all to nuclear power. Kneese's argument is that the moral issues surrounding nuclear power take it out of the positive economic context.

Pearce (1979) questions this conclusion pointing to the normative basis of all SCBA (the overriding significance of current income distribution and current preferences in determining money values of costs and benefits, and the SDR). His rejection of SCBA arises because he gives greater importance than Jeffery to the questions of civil liberty in an increasingly nuclear powered society, and of weapons proliferation.

Pearce quotes Page (1977a) as perhaps offering a means of dealing with the bias inherent in the NPV rule. Page's view is that since future generations will suffer costs from nuclear power, their preferences should be given weights equal to those of the current generation. The chosen outcome would benefit the maximum number of generations which is clearly an application of the Rawlsian notion of optimality. Since it requires information that could never be available, one means of approaching the solution would be to set the discount rate at zero and so sum the costs at levels considered accurate today.

Jeffery's solution is similar but more powerful. He argues that the future costs of the nuclear power programme should be discounted using a negative discount rate, hence an increasing discount factor. (There has to be a cut-off point to prevent the latter from becoming ridiculously large - beyond the cut-off point the discount factor remains constant at its cut-off point value). Jeffery leaves benefits being discounted in the standard CEGB manner but has now presented a means of both highlighting and penalising costs which arise far into the future.

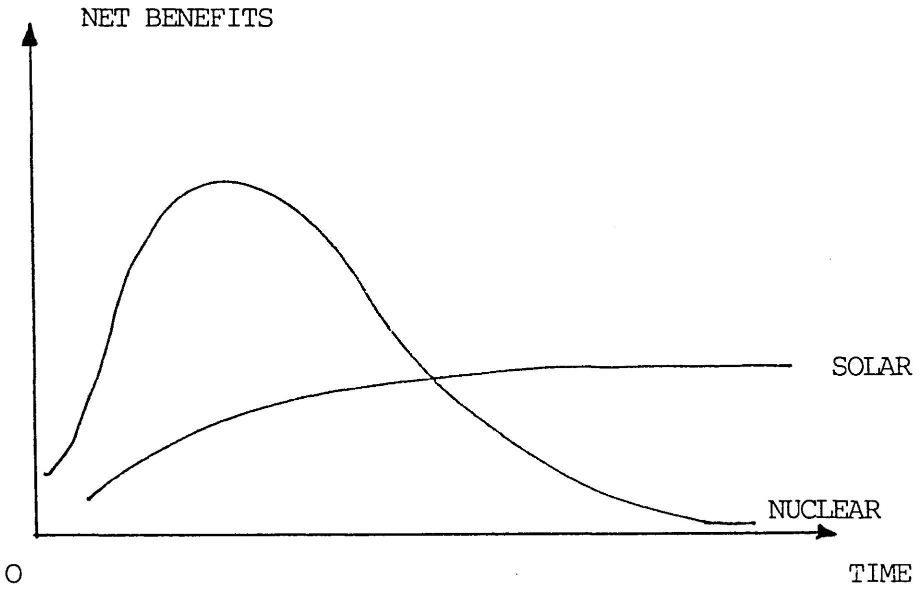
This is not a new approach. Haveman (1965) considers the problem of differences in the uncertainty associated with the costs and benefits of projects given general risk aversion. The latter requires giving greater weight to future costs, hence he suggests discounting benefits and costs separately. For the former the discount rate should be the riskless rate plus a premium, and for the costs it should be below the riskless rate. The relative size of these adjustments depends on the relative uncertainty of the costs and benefits.

Arrow and Lind (1970) also include this possible course of action in an example recommending different discount rates for costs and benefits where the costs are borne largely by the government and the benefits accrue to individuals.

The effect of this can be seen using an example from Page (1977b). He considers investment today in two alternative means of producing electricity: solar and nuclear. Solar has very high initial costs but minimal costs later; nuclear has much lower initial costs but later in life starts to produce the waste/decommissioning costs that concern Jeffery. The comparison is shown in Figure IV.18.

Figure IV.18

Net Benefits of Alternative Projects Over Time



The discounting procedure selects the nuclear option because of the high early loading of net benefits. Jeffery's solution would shift the whole nuclear net benefit curve downward, leave the solar curve unchanged and switch the decision. The bias in the discounting procedure which (in Jeffery's view) makes it worthwhile to push costs as far as possible into the future, is shown clearly, and corrected.

Jones (1984) argues that Jeffery's approach is simply wrong, both in its claim that nuclear power should be treated differently because it has unique features, and in its conclusions about CEGB behaviour.

There is nothing unique about the fact that nuclear power has costs arising in the future - so do coal fired power stations, which may be contributing to acid rain damage to the environment of Northern Europe, and are contributing to the atmospheric build up of carbon dioxide (- see Chapter VI).

Second, Jeffery's claim that the industry is encouraged to push costs forward in time to render them trivial by discounting is also dismissed. Jones has two arguments. One, that pushing costs forward is precisely the behaviour that everyone adopts - preferring to delay payment for as long as possible. Two, that the alternative which must be presumed to be recommended by Jeffery is to bring all costs forward and, for example, build waste repositories at the same time as the reactors whose fuel will eventually fill them are constructed. If this second point were valid it would clearly point to an absurdity in the Jeffery case. However, it is enough to point to the difficulties of dealing with costs which arise in the future without necessarily arguing the discounting provides incentives for delay. Indeed if such incentives do exist the correct procedure would be to consider the significance of the costs if undelayed - not to bring them to the present.

The essence of Jones's argument is that discounting is an acceptable investment appraisal technique. There is nothing unique about nuclear power which is, in fact, highly capital intensive compared to coal and so suffers from the discounting procedure. Given that the method works satisfactorily there can be no justification for the sort of "arbitrary adjusting" suggested by Jeffery.

Some of the arguments discussed above are also used by Jones:

(a) If waste/decommissioning were considered "unique" then (i) a preferred solution would be to insist that the industry dealt with the problem within a given time period, (adjusting the NPV rule to a payback rule) or (ii) adopt the Freeman (1977) solution of investing now to provide for future costs.

(b) Jones quotes the discounting procedure of the National Radiological Protection Board. This is to use a STPR (of 0% to 3%) for discounting public detriment as this is a social cost, and a commercial rate (of 5%) for occupational detriment which is a financial cost to workers whose wage already covers any risk. This is the "different rates for different risks" argument.

(c) Jeffery refers to Mishan (1982a) (discussed earlier), to give weight to his argument that the NPV rule is meaningless in the context of nuclear power. Jones uses the same reference to argue the suitability of discounting. He assumes that future generations will be wealthier in both money and technology. Costs which appear substantial today will, on this view, be valued less in the future and may even be trivial if the technology advances sufficiently to deal completely with the problems. The implication is that discounting current estimates of future costs may, if anything, overstate their significance, so the problem of not knowing the preferences of future generations may be ignored.

In the case of nuclear power there are, thus, two directly opposite methods of dealing with investment appraisal. Jones (1984) argues that cost benefit analysis in its standard form may be used with equally standard discounting rules. Pearce (1979) argues that SCBA may not be undertaken for nuclear power where the ultimate choice is "ethical and political". Jeffery (1983) believes that adjustments must be made to the discounting procedure before SCBA is acceptable. This debate is linked directly to the question of irreversibility and intergenerational equity.

IV.4 IRREVERSIBILITY AND INTERGENERATIONAL EQUITY

IV.4.1 The Option Value Approach

In 1964 Weisbrod introduced the concept of 'option value', which, in the context of nuclear power, may be seen as an additional cost that should be added into the cost-benefit calculations to account for the fact that once undertaken, nuclear power projects involve irreversible change in the environment. Weisbrod's own example was of a privately owned park where the admission fees were inadequate to keep the business viable. Because of the nature of the park, individual customers' visits would be likely to be infrequent and uncertain in their timing; yet once closed down and used for some alternative purpose, the area could never again become a national park, or could be only at exorbitant expenditure. The aim of Weisbrod's article is to point out that many people - a great number of whom may never have used the park - would value its continued existence. That is, their views represent an option value - their preparedness to pay now for the option to be able to use the park's facilities in the future. However, a private owner has no obvious means of collecting the option value from the future potential park users; as a result the park remains unprofitable, and the owner shuts the business. Yet it is quite feasible that the sum of actual payments plus the option value would be quite adequate to cover costs, in which case keeping the park open is, from a social standpoint, an efficient solution.

Even if the owner were a perfectly discriminating monopolist, able to extract the full willingness to pay from each consumer, this result holds. Cicchetti and Freeman (1971) extend Weisbrod's analysis to demonstrate this, and show that option value may be considered a risk aversion premium. (Weisbrod himself speaks of an analogy between the concept of option value and investment: any given individual who is a potential visitor to the park has an option value, even though the visit may never take place; similarly, the payment of an insurance premium is the purchase of protection against possibly substantial loss, and yet that protection may never be used).

Cicchetti and Freeman take a commodity with the same properties that Weisbrod outlined for one which would be likely to display option value. These are (i) that (at least some of) the potential consumers are uncertain about their pattern of future demand; (their demand is likely to be infrequent and may cease altogether);

(ii) the owner of the commodity - even if a perfectly discriminating monopolist - is unable to collect the option value;

(iii) the production of the commodity may cease in the immediate future (the park may be used for alternative purposes), and reinstatment is impossible (except at enormous cost).

All individuals are assumed to be risk averse and uncertain as to whether or not they will wish to consume the good in the future. Assume that the probability that a good, X, will be demanded is 0.5. The consumer must decide whether to purchase today from current income

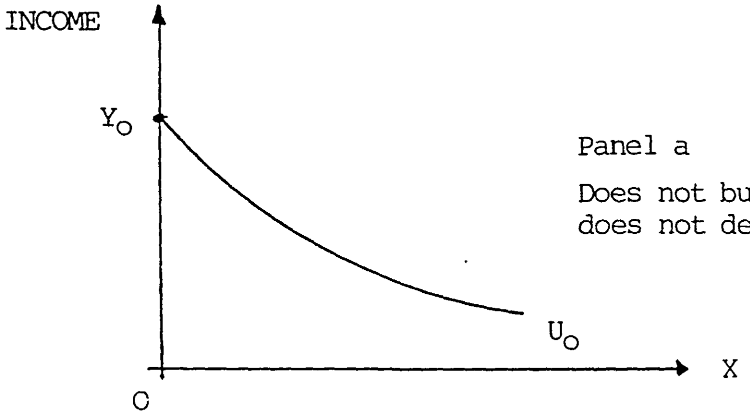
Y_o an option, price P, to buy good X in the next period. In Figure IV.19 Panel a, the decision is not to buy (hence the budget line is the vertical axis), the outcome is that the good X is not demanded, and the relevant level of utility is found on indifference curve U_o. But if the good is demanded it will not be supplied because the option was not purchased. Hence, the individual must be switched to a new indifference map (panel b) where the relevant curve is U_1, still cutting the axis at Y_o (because the budget line is the axis). But, this does not give the utility level U_o, because the good is demanded yet unavailable. Cicchetti and Freeman say this gives a lower utility of U_1. In Panel c the option is bought, income falls to Y_o-P and if the good is demanded utility would be U_1 ; the good will be available with certainty. Given that the probability of demanding the good is 0.5, the expected utility is

$$0.5\ (U_o + U_1) = U^*$$

This means that a perfect price discriminating monopolist could charge a price of 0.5P for the option as that is the expected consumer surplus.

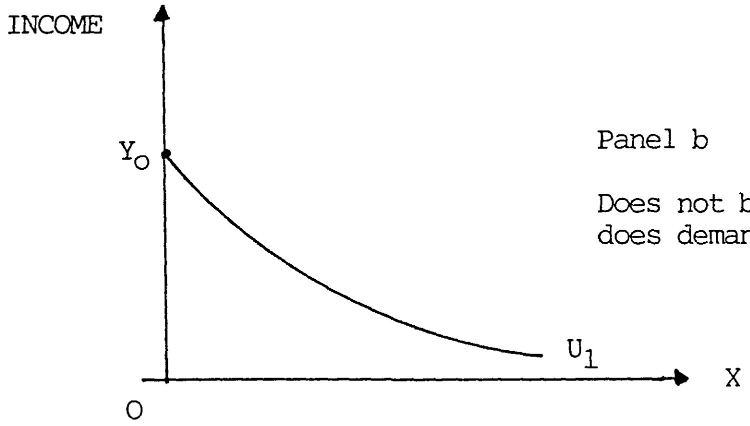
Figure IV.19

<u>Option Value</u>



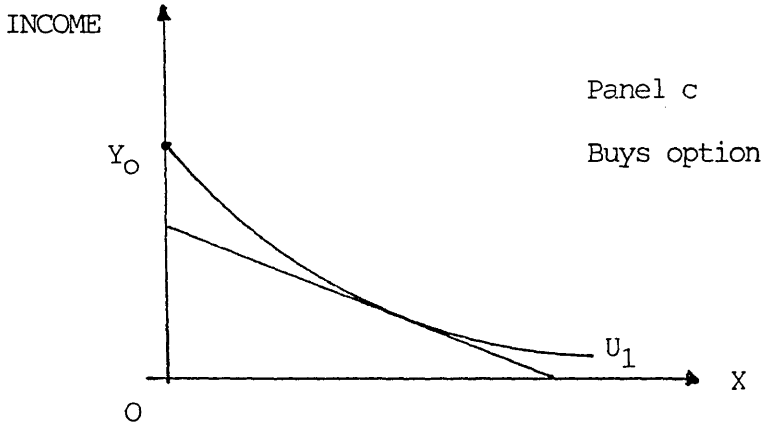
Panel a

Does not buy option;
does not demand X



Panel b

Does not buy option;
does demand X



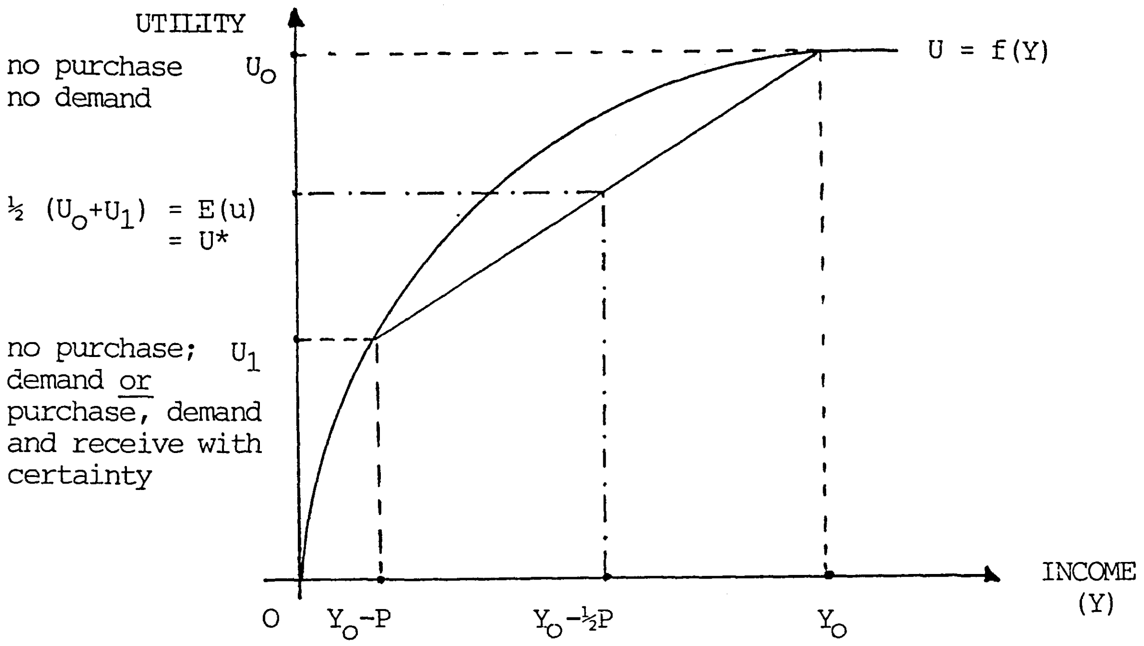
Panel c

Buys option; does demand X

In Figure IV.20 the information from Figure IV.19 is re-presented:

Figure IV.20

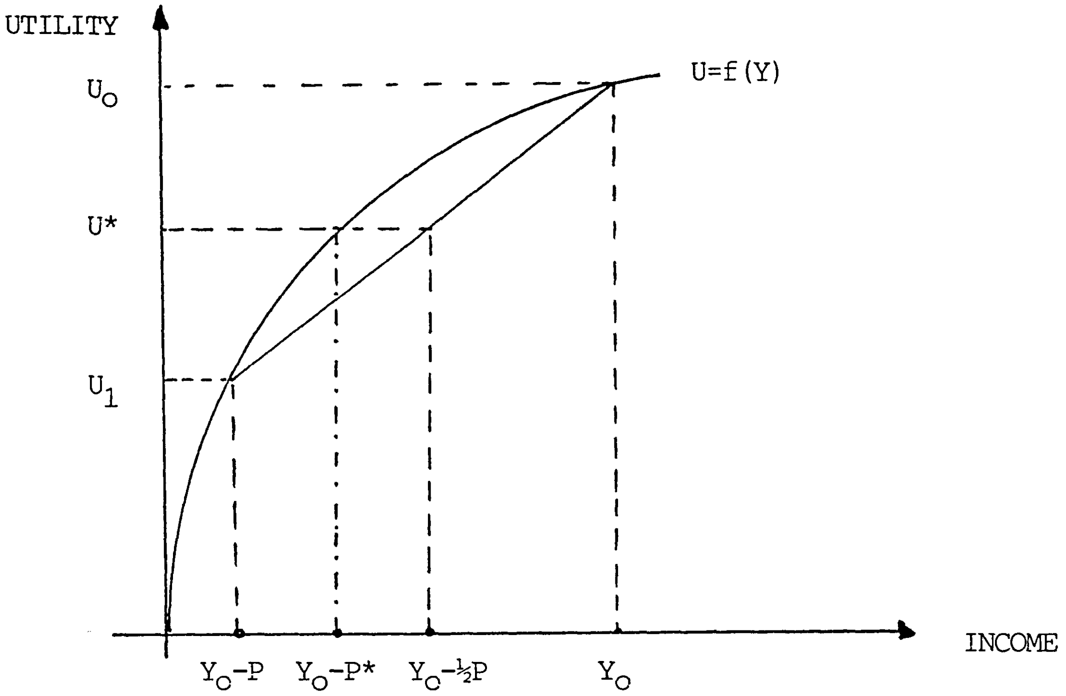
<u>Option Value and Expected Value</u>



The next question is what would the consumer be willing to pay to avoid this uncertain situation? The expected utility is $E(U) = U^*$ and this must be associated with an equivalent expected income of $0.5(Y_o) + 0.5(Y_o-P)$ or $Y_o - 0.5P$. But the shape of the utility function implies that the consumer would be prepared to pay $Y_o - P^*$ to achieve U^* with certainty (Figure IV.21).

Figure IV.21

Option Value, Expected Value and Certainty



Hence, the choices are:

(1) Pay P and achieve U_1 with certainty;

(2) Pay P* and achieve U* with certainty;

(3) Pay nothing and have an equal probability of achieving either U_o or U_1 - whose expected value is U*.

The associated expected income is Y_o - 0.5P.

Hence, the individual is indifferent between paying nothing and paying P*. The difference P* - 0.5P is what Cicchetti and Freeman refer to as the true option value - the premium which risk averse individuals would be prepared to pay to produce certainty rather than live with risk.

IV.4.2 The Option Value Approach to Nuclear Power

The concept of option value has two distinct applications in the context of nuclear power. Haveman (1977) has written:

> "when individuals are uncertain about their future use of a facility (or when the supply of a facility is uncertain), if an adverse impact on the facility is irreversible, and if the individuals are risk averse, an extra cost - called option value - must be added to the expected value of future damages" (24).

The construction of nuclear power plants causes an irreversible change to the environment, as Jeffery (1983) argues. His particular concern lies with the implications of discounting for projects having extremely long terms costs, but the point relevant here is that radioactive waste treatment and decommissioning will involve generations hundreds (perhaps thousands) of years into the future - even if all power stations were closed down immediately. Hence, the power programme represents an irreversible creation of radioactive waste and irradiated plant. Similarly Arrow and Fisher (1974) write:

> "The expected benefits of an irreversible decision should be adjusted to reflect the loss of options it entails". (25)

Pearce (1979) points to the two applications of this analysis:

> "... to opt for nuclear futures or not to opt for them may both be decisions which impose irreversible consequences on probably many generations".

Thus, the first area where option value is relevant to nuclear power is in the implication that the decision to undertake such a power programme brings irreversible change; and such change requires that any attempt at social cost benefit analysis must recognise the irreversibiity explicitly by raising the cost calculations.

Pearce (1977) discusses the distinction between reversible and irreversible projects. The former would be one which could, at any time, be totally expunged, so that no current effect or structure of the project remained. Could it be argued that nuclear power actually falls into this category? Clearly the waste will always have to be stored somewhere, but the industry argument is that this will be achieved with safety:

"On the basis of its own studies and those undertaken elsewhere the Board is confident that the tasks involved in the decommissioning of nuclear plant can be carried out safely and successfully, and it has made financial provision for the costs involved". (27)

However, Pearce strengthens the 'reversible' definition by arguing that a cautious approach would require current technology to be capable of undertaking the reversal. Reliance on unknowable technological development to occur and be able to deal with presently insoluble problems renders the project irreversible in this view. Thus, waste and decommissioning do imply irreversibility. Cost estimates have been made for measures to deal with these aspects of the programme, but the irreversibility itself is a cost which, once imposed, is impossible to remove; the result noted by Pearce (1977) is "... a double cost (which) should surely attract an extra penalty" (28). And that penalty is measured by the option value.

It is also true, as Pearce (1977), (1979) notes that this cautious definition "... could easily become heavily restrictive", and could imply a refusal to take decisions which would have serious negative income repercussions for future generations. This is discussed later as the second application of option value in the context of nuclear power.

Fisher (1973), and Arrow and Fisher (1974) both take the Cicchetti-Freeman argument on option value in an uncertain world and deal with its implications for irreversible projects. Both are concerned with the implications that option value has for the Arrow-Lind (1970) result that public sector investment should be evaluated only on the basis of expected returns as individual (and aggregate) risk premiums go to zero as the risk is pooled over a very large number of people. Haveman (1977) argues that option value is a sort of risk or uncertainty cost which will become "socially irrelevant" if the Arrow-Lind theorem holds. In fact both Fisher and Arrow-Fisher contradict Haveman's argument.

The Arrow-Fisher (1974) example is of a piece of land whose benefits of preservation would be irreversibly lost by a potential development. They show that the investment criterion in such a case has to be adjusted to take account of the uncertainty over the costs and benefits of the development. Specifically the adjustment - a reduction in the net benefits attributed to the development - is undertaken when the irreversible change is learnt over time and leads to alteration in the expected values attributed to development and preservation. Their conclusion is noted above, and a particular element of it is that perceived benefits in the first period may be positive, but development is nevertheless delayed, perhaps indefinitely. This has implications for Page's argument (1977 a and b) that decision rules alternative to discounting could preclude nuclear investment now.

Page's proposition is that technologies other than nuclear power are not yet competitive and in the short run would be rejected. In time, however, renewable, benign technology could produce greater net benefits by operating without the social costs of waste and so on that will accompany the nuclear programme. The long term benefits would, in some methods of calculation, outweigh the immediate presumption in favour of nuclear power - but not when investment appraisal is undertaken by discounting. Furthermore, the NPV procedure having (wrongly) chosen the nuclear alternative also precludes further development of the other technologies since research funding will clearly be devoted to the chosen programme. Page's arguments in favour of different methods of investment appraisal are discussed later.

Fisher (1973) is concerned to test the Arrow-Lind theorem's conclusions when an investment project also involves uncertain environmental externalities. His analysis concentrates particularly on cumulative and/or irreversible effects such as increased mortality rates, which fall on a specific group of people, whose real income is clearly affected as a result. He shows that in such a case risk does affect the Arrow-Lind result and the cost estimate for the investment must be adjusted. It will have to cover both the expected environmental damage costs (which is, in itself, nothing more than internalisation of an externality and so not an implication for the Arrow-Lind theorem), and the compensation necessary for the group bearing the increased risk. Theoretically that risk could be transferred to the entire community (and so rendered negligible) by private insurance markets. However, a central element of the Arrow-Lind theorem is the point that such markets do not exist because of transactions costs, moral hazard, (and the impossibility of satisfying the Arrow-Debreu conditions for general equilibrium). Also it may be impossible (because of the transactions costs of identifying the losers and measuring their losses) for the government to take on the role of the (theoretical) insurance markets and thereby reduce the risk to zero. Thus the presence of transactions costs implies that the affected group must continue to bear the risk; this disproportionate cost must then be reflected by adding both the expected environmental damage costs and the risk-compensation payments to the overall cost estimate for the project.

Thus, the conclusion is that investment decisions with irreversible consequences represent a curtailment of options for future (generations') behaviour. The option value - the value of expected irreversible damage costs - needs to be added to the cost-benefit analysis. If such a cautious procedure is followed it will have the effect of preventing the acceptance of projects imposing a level of costs on future generations which would lead those generations to cancel the undertaking. Caution requires current rejection of such projects precisely because it will be impossible to cancel them in the future since some of their effects are irreversible. Hence Krutilla and Fisher (1975) "it will be efficient to proceed very cautiously with any irreversible modification to avoid the approval of activities generating environmental damages which from 'tomorrow's' perspective should have been disapproved" (29). It seems clear that a nuclear power programme of necessity causes irreversible change to the environment. It produces waste which must be stored, (reprocessed), transported, and made ultimately disposable. This requires extremely long term repositories and, however much of the fuel cycle is undertaken in a particular economy, some civil liberty is lost as areas become forbidden (and perhaps protected by armed guards). Waste disposal sites become unavailable to the general public for any other purpose for - what is effectively - ever. The central question of this section is the significance of this for the investment decision.

Jeffery (1983) writes of the "unique long term costs (of nuclear power) extending over many generations", and Pearce (1979) has a list of what must be included in the "costs of a nuclear future": radiation hazard; disposal of high level radioactive waste; civil liberties; accounting for the last kilogram of plutonium; the risk of nuclear proliferation.

Jones (1980), in contrast, dismisses both the civil liberty argument: "the marginal effect on liberty of one more protected site is minimal"; and the problems of waste disposal and reactor decommissioning: "studies have been conducted in many countries for many years ... experts are confident of no risk" (30). The implication is that the cost estimates need to cover merely the expected values of the disposal/decommissioning costs. The proliferation issue is also rejected as irrelevant to the decision making process: the U.K. already has nuclear weapons; and a new U.K. civil reactor will contribute neither to the U.K. weapons stockpile, nor to any other. Marshall (1980a) goes further, arguing that the presence of a fast breeder reactor would actually make society safer by both burning plutonium and by making the fuel it uses so powerfully radioactive that no terrorist could possibly approach it. This view is also expressed by the Department of Energy (1977): "... recent theoretical studies have suggested that adaptations of the fast reactor fuel cycle could eventually be made even more resistant to proliferation than thermal reactor fuel cycles which do not include reprocessing" (31).

However, the conclusion would seem to be that the nuclear stations and waste do represent an irreversible change to the environment and hence, the analysis of option value presented above is relevant. To the extent that social cost benefit analysis can be undertaken at all in the context of nuclear power, the cost figures require an upward adjustment. As Fisher (1973), and Krutilla and Fisher (1975) point out, however, the theory "does not spell out the precise quantitative adjustments to estimated benefits and costs that would be required". Nevertheless, "the direction of the required adjustments, if not the magnitude, is apparent" (32).

A further difficulty in this area is that often the measure of the burden imposed on the environment is simply the emmission rate of a pollutant, normalised to a quantity of electricity produced. That is, something is known about how much waste is put into the environment, but far less about the effects when it gets there. This lack of knowledge of the damage function thus compounds the complexity of attaching monetary costs to option value (see Chapter VI).

IV.4.3 Option Value and the Pace of Investment

If the above advice were followed it would evidently imply a slowing down of any nuclear investment programme, because of increased costs. Thus, a typical cost-benefit analysis such as the USAEC study (1974) takes the position that the measure of the benefit of electric power generation is simply the existence of that electric power. Benefit is defined to be a quantity of electricity. USAEC do not consider the question of whether or not electric power should be produced, but instead concentrate on the relative costs of producing it by different means. Thus, the study becomes a comparison of the risks and costs of producing electricity in alternate systems, and adding option value costs to one must restrict its attraction. A similar position is taken by the CEGB (33) in arguing that the relevant economic appraisal is to choose that generating capacity which will give the lowest overall cost and meet the demand; revenue is not part of the calculation as the CEGB has a statutory duty to meet the demand for electricity. However, the 'slow-down' course of action also relates to the concept of option value. The slow-down may be erring on the side of caution in the sense that future generations will find that the irreversibilities mentioned above prove to be of no significance - that the atomic energy industry's view proves correct. In that case, future generations will find that they would have preferred today's investment to be greater: their wealth and growth rate will suffer because of today's mistakes about their preferences and technological abilities. Hence, caution today removes options from future generations. The types of options considered relevant in this view are summarised in the quotations following:

(1) Department of Energy (1976): "Examination of the individual scenarios points to three main themes:

> (1) the key importance of conservation...
> (2) the essential nature of an expanded coal industry
> (3) the significance of nuclear energy (and in particular the fast reactor) to a United Kingdom economy with aspirations of long term growth" (34).

(2) D. le B. Jones (1982): "Basic energy policy objectives in the U.K. ... [include developing] those sources of energy that are necessary to meet longer term requirements - most notably coal and nuclear power".

(3) Department of Energy (1970): "... in most perceived views of the future nuclear power will be essential in meeting our energy demands. However, if these expectations are to be fulfilled our nuclear construction industry must be able to build reliable reactors; to achieve this we must maintain a commercial ordering programme which will enable our nuclear industry to keep together and build up the experienced teams that are essential if the rate of construction is to be accelerated in the final years of this century. Without these strategic considerations it would be difficult to justify maintaining the momentum of our nuclear programmes particularly at a time when the immediate outlook does not reflect our long term need for a nuclear-based electricity supply industry". (35)

(4) Central Policy Review Staff (1976): "The study concludes that on grounds of the country's present industrial strategy, the need to sustain employment and the balance of payments, there is a strong case for maintaining in the United Kingdom a power plant manufacturing industry which can supply the home market and compete successfully overseas. To achieve this "effective action" would have to be taken by both the Government and the industry. This would involve a change in the present plans for power station ordering and major changes in the structure of the industry". (36)

"...uncertainties about present policy on United Kingdom nuclear power stations - particularly the choice of reactor - need to be resolved as early as possible" (37) because:

"It is likely in the view of the electricity supply industry that in the next 25 years most new power stations built in this country and throughout the world will be nuclear. The United Kingdom power plant manufacturing industry will therefore need to be capable of supplying plant for nuclear power stations as well as for conventional fossil-fuelled stations ... The urgency of this decision (on reactor type) for the future welfare of the boiler makers cannot be over emphasised". (38)

The above points serve to demonstrate that option demand for nuclear power exists to guarantee society does not suffer from an energy gap; to protect turbine and boiler manufacturers (and this reinforces the energy gap argument); to allow technological knowledge and ability to grow; and - perhaps all-importantly - to permit future economic growth. The justifications of these views, particularly the latter, are discussed in Chapter VI. However, the conclusion here must be that the concept of option value is significant for social cost benefit analysis of nuclear power - but that it operates for both costs and benefits. Absolute quantification is evidently as difficult a task as Krutilla and Fisher say; relative quantification is now seen to be necessary, and perhaps as difficult.

IV.4.4 Intergenerational Equity

The problems of risk, uncertainty and irreversibility lead to consideration of intergenerational equity. This is partly the concern of the debate emanating from the papers by Jeffery (1983) and Jones (1984) on the 'correct' rate to use for discounting in investment appraisal. Jones argues that "average real returns accepted on established private investment may be as good a measure as any of the social time preference rate". He goes on to make the case for a standard discounting approach to nuclear investment, which, therefore, has, as one of its features, both a recognition of the need to consider future generations, and a satisfactory reflection of what society's current consideration is. It is important to note that that view will change and such changes have been evident in the past. Elsewhere Jones (1978) gives the example of public antipathy towards the introduction of smokeless zones changing to enthusiastic acceptance after their adoption, when their benefits became apparent.

Similarly, Doeleman (1985) considers the choice of discount rate. He points to the 'conservationist' view that society's concern should be for the (indefinite) continuity of the environment and future generations; the implication being that discounting should be rejected and all future values summed at their absolute (estimated) levels. But Doeleman dismisses the argument as unacceptable - all decisions must use the actual prices produced in the market and reflecting consumers' willingness to pay; and the interest rate is simply another one of these prices. However Doeleman's main point on cost benefit analysis as it affects the environment is that 'macro-environmental standards' should already have been established; hence, using market prices avoids arbitrary or contentious adjustments for specific issues. This approach has similarities to the conclusion of Krutilla-Fisher (1975) that current generations, if uncertain as to how future generations will view some of the consequences of today's actions, should avoid approving projects which have the property that future generations will look back and say they should have been rejected. There is a range of means of dealing with this conclusion.

The first is to refer to the concept of option value and increase the estimate of expected value of damage. Alternatively Jeffery (1983) proposes an adjustment to the discount rate on costs. Clearly, the effect of these could be made identical.

The second is to consider what is being suggested from the viewpoint of criteria for maximising social welfare.

The Krutilla-Fisher conclusion is another way of stating the Scitovsky restriction on the Kaldor-Hicks criterion for welfare improvement; (see Dobb (1969)). The latter essentially argues that what is known about a prospective two-period project are the current relative prices P_o, current quantities Q_o, and estimates of the future quantities Q_1, once the project has been implemented. Some people inevitably suffer, hence the Pareto criterion rejects the undertaking. This excessive caution is relaxed by the Kaldor-Hicks rule that the project may be accepted if $P_oQ_1/P_oQ_o > 1$. From the perspective of the current generation the value of future output (valued at today's prices) has grown and a reallocation of that output could notionally be made to recompense those who lost. Hence, the "national dividend" has risen, and society's welfare has grown; accordingly the redistribution to the losers remains notional not actual. Scitovsky showed that there is a possible paradox. If the project is non-marginal, relative prices will alter as quantities alter, and there is a fourth, relevant piece of information P_1. It may now be possible that although $P_oQ_1/P_oQ_o > 1$, it is also the case that $P_1Q_1/P_1Q_o < 1$. Now from the perspective of the future generation, valuing quantities at the prices relevant to them makes the project undesirable. To avoid this paradox, Scitovsky argued for a change in the Kaldor-Hicks Criterion; for a project to be accepted the following two conditions must hold:

a) $P_0Q_1/P_0Q_0 > 1$ and b) $P_1Q_1/P_1Q_0 \nless 1$
and this is the result Krutilla-Fisher insist should be guaranteed by adjusting costs when there is uncertainty. An alternative implementation (since P_1 is unknown in the initial period) is clearly conceptually difficult and will be discussed later.

The third interpretation is found in the arguments of Page (1977 a and b). In the latter reference Page argues that society can decide on future provision in many ways and is absolutely not constrained to use discounting. Since his particular concern is intergenerational equity he points out that discounting is essentially irrelevant to that concern; instead it relates to efficiency over time. Yet the ramifications of nuclear power are peculiarly involved with "potentially enormous transfers of well-being over very long time horizons", implying that equity could be of paramount importance. Page considers the possibility of "Pareto dominance", when, for example, choosing between two projects. This requires the net benefits from one project being equal to or greater than those of the other in all years, and greater in at least one. He rejects this as the intergenerational equivalent of unanimity voting, and hence a "rule of paralysis".

Instead Page presents a Kaldor-Hicks type argument with his "almost - anywhere dominance" decision rule: majority voting extended to an intergenerational framework. His example requires consideration of a large number of generations and comparing net benefits in each generation. Discounting, (even at a zero rate) is not undertaken as the net benefits are not summed - just compared at each point. Then the project offering superior benefits to the greatest number of generations is chosen. In Page's example of a choice between a nuclear and a solar project, (see above), this involves the first few generations foregoing the clearly (much) higher net benefits of the nuclear option so that future generations may enjoy the (then) superior net benefits of the benign (yet initially expensive) solar option.

It is evident that this proposition has certain impracticalities - how many generations are to be considered? (Plutonium has a half life of 25,000 years and is biologically toxic for 250,000 - does that indicate the number?). And how many generations should accept austerity. The point is that this criterion from Page emanates from the work of Rawls (1974), and gives each generation an equal vote. Rawls' theory of justice envisages policy decisions being made by a group whose members are unaware of their actual position once the decision is made. This provides a "veil of ignorance" and leads to a "maxi-min" solution, whereby the welfare of the poorest member (who is unknown to the decision makers) dominates. Page's argument extends this to an intergenerational context and considers the pooled votes of average representatives of each generation, but representatives who are kept unaware of the generation of which they will actually become members. Doeleman (1985) regards Page's work as the intertemporal version of intratemporal Rawls.

The apparent impracticalities arise because of this; and because it is a deliberate attempt to reject discounting. Whereas Page's Rawlsian approach treats each generation as having equal rights, and so accepts projects on a majority rule vote, discounting may be seen as the dictatorship of the present generation. As such it is unacceptable when viewed from the standpoint of intergenerational equity. Thus, Page has considered unanimity voting, majority rule and dictatorship, but in an intergenerational context. The reason he regards discounting as a form of dictatorship is that it renders what are actually benefits and costs to future generations as rewards to the present generation. The latter will obviously seek to maximise its welfare by maximising these net benefits, and in doing so will, as an unconsidered and incidental result, make decisions that provide for the future. To the extent that the present generation is altruistic or cautious, then more will be available for the future; but that cannot be guaranteed, and anyway does not negate the implication that by maximising its own net benefits - the sum of present and discounted future net benefits - a present generation using a discounting decision rule is acting as a dictator. This approach does not dismiss discounting entirely: it should be used as an efficiency criterion. Once it has selected the set of efficient projects, some equity rule must select amongst that set. But, Page argues that there is little work available on such rules.

Collard (39) suggests a means for avoiding the practical difficulties inherent in Page's rejection of discounting as a means of guaranteeing intergenerational equity. He, too, argues that the straightforward NPV rule is one instrument being used to (attempt to) achieve two targets: equity and efficiency. The solution he proposes is to use discounting - presumably on the standard efficiency grounds - but to attach generational weights to individuals, so that today's view of the relative importance of net benefits to different future generations is made explicit. The overall net benefit of any project is then the sum of the weighted discounted individual net benefits. Thus, the present value of £1 in year t is:

$$\sum_{b=0}^{b=t} N_{bt}.W_b.(1 + R)^{b-t}$$

where

b = individual's birth date

W_b = the weighting function

N_{bt} = the proportion of individuals born in year b and alive at t

R = the social discount rate

So beginning in year zero with generation zero, the value for the next year is:

$$N_{01}.W_0.(1 + R)^{-1} \quad ;$$

and two years ahead requires two pieces of information - the value for generation zero:

$$N_{02}.W_0.(1 + R)^{-2}$$

plus the value for generation one:

$$N_{12}.W_1.(1 + R)^{-1}$$

Three years ahead requires values for generations zero, one and two:

$$N_{03}.W_0.(1 + R)^{-3} + N_{13}.W_1.(1 + R)^{-2} + N_{23}.W_2.(1 + R)^{-1}$$

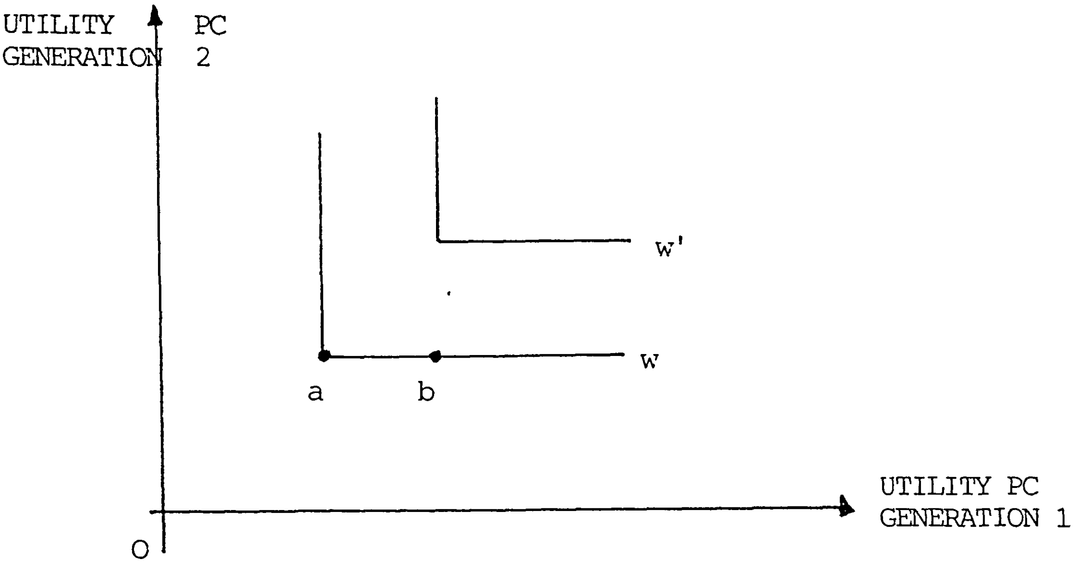
Suppose it were decided to favour future generations. This is done by allowing W_b to increase as b increases, so $W_2 > W_1 > W_0$. From the final sum in the example above, it is clear, given this value judgement about the future, that not only does the weight favour future generations, but the discount factor acting on the weight is also smaller the further forward the generation.

Solow (1974) discusses the problem of intergenerational equity in the context of another form of irreversibility - the depletion of a non-renewable resource. He rejects discounting and uses instead a strong

form of the Rawlsian principle of justice extended to cover the intergenerational example. Solow claims his analysis is "plus Rawlsien que le Rawls" since Rawls himself is uncertain when dealing with intergenerational problems. His proposition seems to fall down when faced with the impossibility of current generations having welfare levels raised by actions of future generations. "We can do something for posterity, but it can do nothing for us". (40)
Solow's maxi-min criterion concentrates on the generation having the lowest utility in each possible consumption path. The total welfare of any given consumption path can only be raised by raising the utility of that generation and guaranteeing that no other generation now drops below it. This is clearly similar to what Page is suggesting. Again representatives of each generation are seen as meeting to draw up the social contract; the timing - earlier or later - of the generations is then "arbitrary" and so the result of equality of consumption becomes inevitable, and, as Mishan (1977) argues, amounts to classifying the intergenerational social welfare function as L-shaped: Figure IV.22:

Figure IV.22

Rawlsian Intergenerational Social Welfare Function



W, W' are indifference curves from the (assumed) social welfare function. Point a represents exact equality; improving the utility of generation 1 by moving to point b is of no relevance. The reason why such a point of equality of utility such as at a arises is that unless there is equality, there is always the opportunity to improve the welfare level of any consumption path by redistributing income in favour of the poorest group. The implication (apart from the unsatisfactorily conservative conclusion that using the Rawlsian principle generates) is that present generations can justify their consumption of irreplaceable resources - hence, their decision to undertake projects with irreversible consequences - provided that they can also contribute to raising standards for future generations by, for example, adding to the stock of reproducible capital. Jones (1978) also makes this point, arguing that current generations' consumption of non-renewable energy sources must be matched by discovery of new sources or of new technology to allow substitution. His particular preference is to establish fast reactors - as well as investigating other alternatives. However, the establishment of such a technology creates another irreversibility which is part of the reason for Page's advocacy of a Rawlsian principle: it will take up such a large proportion of Research and Development funds that it effectively precludes the investigation of the other alternatives.

IV.5 SUMMARY

This chapter shows that the standard investment appraisal techniques are not generally accepted as accurate in the special case of nuclear power. The particular problems are the long time lag before some major costs (of decommissioning and waste treatment) must be faced and the overwhelming importance of risk and uncertainty. Attempts to accommodate these problems imply adjustments to the discount rate used, and/or discounting costs and benefits separately. The significance of the methods used in investment appraisal lies in the impact the decision will have on future generations. The concept of option value has been applied to the case of nuclear power to demonstrate that questions of irreversibility and equity can be made operational in economic analysis (as opposed to being essentially moral or ethical problems), as the associated option value indicates how cost assessments should be altered. The approach also puts into an economic context statements concerning the need to continue nuclear investment to guarantee energy supplies, to protect the construction industry and design teams and so on.

The following appendix discusses the specific risks which underlie the problem areas covered in Chapter IV.

APPENDIX IV.1

RISKS SPECIFIC TO NUCLEAR POWER

Weinberg (1972) regarded nuclear energy as "on the verge of becoming our dominant form of energy" (41). Because of this he felt that those behind the engineering and technological development had made a "Faustian bargain with society"; this was the offer of relatively cheap and inexhaustible energy in return for "both a vigilance and a longevity of our social institutions that we are quite unaccustomed to". In that article Weinberg reviewed the major problem areas that an expanding nuclear industry would have to face. These include the siting of reactors (clustered in parks or sited separately), and the possibility of reactor failure, where he writes "such complex sequences are hardly susceptible to a complete analysis. We shall never be able to estimate everything that will happen in a loss of coolant accident with the same kind of certainty with which we compute ... even the course of the ammonia synthesis in a fertiliser plant" (42). However, Roberts (1984a) discusses the technique now used to deal with this problem. The solution is to 'undo' the complexity of the reactor by recognising that it is composed of ordinary, well-understood items - such as pumps and valves - whose operating performance has been logged over long periods. Thus, the possibility of plant failure can be pictured diagrammatically as an event tree: an initial fault can be followed by shutdown as the system reacts correctly. Alternatively, a further piece of equipment fails and so leads to the next link in the event tree - system shutdown or a third failure and the next event. Since the parts which may fail have recorded operating experience, the risk assessors can attach probabilities that they will fail - these will be the observed relative frequencies of failure. Hence, any branch of the event tree - for example a (long) series of components failing consecutively - can be given a probability of occurrence.

Thus, although Weinberg's view that we cannot know with certainty what is going on inside the reactor may still be valid after thirteen more years of research, the use of event tree analysis makes it possible to attach a 'risk' to the operation of the plant under whatever circumstances may be desired.

Weinberg's next area is the consideration of waste storage and/or disposal. This together with the operation, maintenance and decommissioning of reactors is what lies behind his claim that the introduction of nuclear power brings with it the necessity for longevity of human institutions. While many of the activities essential to the complex society of developed countries also require a perpetual commitment, (Weinberg notes agriculture as one example), the development of nuclear power could mean "essentially perpetual surveillance" and, in effect, the creation of a "priesthood that forever reworks the wastes or guards the vaults" (43). Weinberg uses the same analogy later, writing of a "military priesthood which guards against inadvertent use of nuclear weapons" (44). The prospect is rendered more attractive by the alternative of permanent disposal of the waste. Thus, Roberts (1984a): "It has been accepted that disposal is preferable to indefinite storage; disposal signifies no need for continued surveillance and no intention to retrieve, though, of course, radiological monitoring can continue" (45). Elsewhere, Roberts (1984b) has written that "monitoring maintenance and surveillance can then be extended for as long as necessary" (46) arguing that the decision to close a repository is a political one and will be considered by a future government. The industry's current requirement is to show that the technology to undertake closure is known so that future generations will not be forced to continue with surveillance of any site.

Weinberg's opinion concurs, although for him this still implies "eternal vigilance ... to ensure proper and safe operation of [the] nuclear energy system" (47) if only to guarantee no future generation mistakenly bores down into the waste repository. In this context it should be noted that Roberts is prepared to use phrases such as: "The activity decays by another factor of 10 in the first few years and, for the next 300 years..."; "The activity has decreased by a factor of over 100,000 within a few hundred years after shutdown"; "... comparatively short lived fission products which mainly, though not completely, decay away in 600 years or so" (48).

These references cover miniscule periods in geological terms, but do highlight Weinberg's contention that social institutions require an unaccustomed lifespan, and Starr's (1982) contention that "The obstacles to this expansion [in nuclear power] arise not from technology but from the inadequacies of our industrial, political and economic institutions to manage this new energy system effectively, nationally and internationally" (49). This is not in any way intended to dismiss Roberts' major point: that the technology to deal with all levels of waste is now available and the final storage - geological isolation - "would prove entirely satisfactory, and the weight of evidence arising from work in many countries led the UK government to stop the drilling programme on the grounds that the option had been proved in principle and that actual operation need not start for many years" (50).

This leads to the next problem area of risk in the development of nuclear power. This is that public perception of risk is often dramatically different from the calculations made by those within the industry. Thus, the OECD Steering Committee for Nuclear Energy (1982) argued for "significant policy level actions by governments", which should include demonstration of "the availability of technologies for all essential aspects of the management of high level and long-lived radioactive waste"; and "the actual risks and the effectiveness of regulation in controlling these risks must be understandable to the public", because "public acceptance is an important factor for the future prospects of nuclear energy" (51). Similarly, the MMC (1981) noted "The CEGB has told us that it expects the safety requirements for new nuclear plant will eventually become settled ... However, it is difficult, perhaps impossible, to predict when this will take place and at what level of requirement, since the public's perception of the risk of accidents seems to be ever changing" (52).

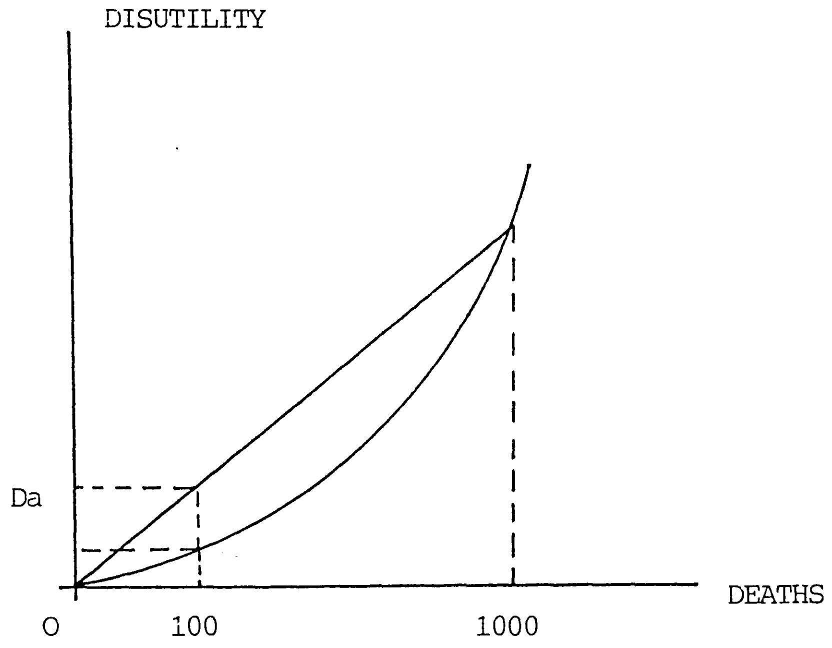
Thus, Roberts (1984a) explains the event tree analysis (above), the assessment of the consequences of releases of radioactivity, and risk studies such as the Rasmussem Report (53). He then notes that despite the fact that "the criteria proposed for safety of nuclear installations ... are well on the conservative side compared with risks normally accepted, or encountered, from other industries ... that is not how they are perceived" (54); in fact nuclear power is often rated in surveys asking people to rank possible risks - smoking, driving, commercial aviation and so on - as "the most risky of all the technologies and activities listed". Yet "it is ... absurd that educated people should be fearful of accidents causing 10,000 or 100,000 casualties arising from nuclear power stations when the probability of such an event is so very low" (55).

This apparent paradox is considered in a large body of literature on risk perception. Fischhoff et al. (1981) write that "people (and, through their combined efforts, society) respond to the risks they perceive, which are not necessarily those calculated by a particular scientist" (56). They then point to a series of reasons why this may be so:- individuals may hold incoherent values because of unfamiliarity with the jargon in which discussion is undertaken. But, although probably true, this is a failure of presentation. Second, individuals may actually hold contradictory values (one set as a parent, another as an employee), or may simply be unable to formulate the relevant problem (having no concept of the nuclear production of electricity). Third, views may be supplemented with new information, but not in a way that permits a decision, or it may be that an individual actually has no opinion without realising it, but when confronted by the questionnaire, responds and is then locked in to that answer. (There is no reason why individuals should have preferences on all possible issues - see Coppock (1981)). While these reasons explain the paradoxical results in risk surveys, it may seem that they generally lead to a conclusion that a safe industry should devote more resources to providing the information that it is safe. However, they can also be used to highlight the possibility that the risks attached to nuclear power are peculiar to that industry, and present special problems to both public and experts. Kasperson (1980) argues that the low probability/catastrophic consequence risks (which Roberts mentions) are analysed not through past experience - the technology is too new - but through models using future estimates where experts can easily differ. Coppock (1981) also makes this point: "risk assessments have to be based on theoretical models, often of phenomena which are poorly understood" (57) because of a lack of historical evidence. But he argues that interpreting these estimates requires a much broader approach than might initially seem relevant - in particular, views on the validity of the value judgements inevitably made in the estimation. Also the (publicised) risks of catastrophe, radiation release and increased cancers are events especially dreaded by the public, leading them to attach greater weight to them. Roberts notes that although these risks are trivial, the dread associated keeps them prominent and overshadows their tiny probabilities. But if they were not publicised, the Fischhoff reasons for inconsistency only become stronger.

In Figure IV.23 the disutility of a particular event - increased cancers for example - is measured on the vertical axis and the size of the event on the horizontal. The shape of the disutility curve represents increasing marginal disutility of increased numbers of cancers.

Figure IV.23

Utility and Catastrophic Accidents



Assume a possible accident is assessed to have a probability of 0.1 of causing 1,000 extra cancers in a given period (this very high risk is simply for the sake of the example). Hence, the expected number of cancers is 100, and the associated disutility is found from the chord Oa to be Da. This is clearly greater than the disutility associated with an event that caused a certain 100 deaths in the period. While this example is extreme, it illustrates the point that people may simply not be prepared to contemplate huge nuclear catastrophes even with tiny probabilities. The consequence is the need to evaluate how individuals decide on the relative safety of particular proposals. In the 1978 Dimbleby Lecture, Lord Rothschild argued in favour of an index of risk, ranking activities or events by risk of death per year (or any time period). He began the lecture: "There is no point in getting into a panic about the risks of life until you have compared the risks that worry you with those that do not - but perhaps should", and notes that "far more row is made about the possibility of a major accident at a nuclear power station than about death from influenza" (58); yet influenza occurs far higher up the index than does the nuclear accident, (Rothschild's figures being 1:18,000 and 1:1 billion).

This approach ignores, however, the additional assessment individuals may make when considering a risk: the magnitude of the threat to society that the event could impose. Arguably this is of primary importance, hence the diagrammatic example above. Certainly the work of Thomas and Otway (1980) gives strong backing to the view that individuals have a multidimensional perception of risk not catered for by the Rothschild approach.

The background to the Thomas and Otway article was the Austrian government's publicity campaign and referendum on the introduction of the Zwentendorf nuclear power plant. Thomas and Otway used survey analysis to investigate public perception of five energy systems: nuclear, coal, oil, hydro and solar. Among the survey conclusions, fossil fuels were seen as more environmentally threatening than nuclear energy, but only the latter was perceived as the possible cause of psychological and physical risks (such as "accidents affecting large numbers of people" and "exposure to risk without personal control").

The overall conclusion was that risk perception is a complex, multidimensional phenomenon, so that setting, for example, strict health limits affects only one dimension and so fails to deal with the overall view of the project risk. Furthermore, Thomas and Otway argue that "acceptable risk will vary from one technology to the next" (59), so that the technological Rothschild-type solution of setting standards based on statistical evaluation of risk already tolerated by society fails twice. This is not, however, to dismiss it entirely: it should still serve to provide an "upper limit on ethically responsible risks, which must not be exceeded - it is a necessary but not sufficient condition that the estimated risks of new technologies be less than this upper limit" (60).

The multidimensionality of risk is also raised in Otway, Thomas and Maurer (1978) where they argue that "the nuclear debate is not really concerned with costs and benefits alone in the usual manner" (61). The debate becomes a focal point for many social concerns and issues, as evidenced by the Austrian government's publicity campaign of debates on energy options which quickly became dominated by opposing pressure groups which effectively polarised the issue (Thomas and Otway (1980)). The debate also centres on the social and political institutions implied by nuclear power; the possibility of increasingly centralised and strengthened technocratic elites and bureaucracies; and on who has, or should have, the political power to make decisions with such consequences. Thus, Weinberg's 1972 discussion with its explicit concern over social institutions is shown to be central to the debate on risk. Roberts (1984a) seems to dismiss these extra dimensions as relevant for consideration in other, political areas; but the implication of risk perception analysis is precisely that these dimensions explain why setting standards with miniscule failure probabilities (and correspondingly exceptional expenditure on safety devices and systems) fails to satisfy the public.

The third risk area is that of the possibility of weapons proliferation. "Nuclear energy generates public concern exceeding the actual risk involved because anxiety over nuclear war is either 'displaced' ... or 'extended' ... to the commercial uses of nuclear power" (Kasperson, 1980). Pearce (1979) regards proliferation as sufficiently contentious and complex as to render cost benefit analysis impossible in the case of nuclear power. Lonnroth and Walker (1979) point out why the connection between civil and military nuclear developments is so often made: "The first British and French reactors were constructed specifically to produce spent fuel that could be reprocessed to yield plutonium for bombs ... and reactor programmes remained dual purpose until well into the sixties" (62). In their view the availability of electricity from the nuclear stations only became important in the late 1950's following the Suez crisis and fears for oil supplies, and similar energy scarcity worries caused by a feared inadequacy in coal output. They go on to argue that (worldwide) civil nuclear industries were established as independent by nations: (i) renouncing all claims to weapons linkage; (ii) accepting comprehensive IAEA safeguards; (iii) signing the Non Proliferation Treaty. This is rather too general a position to apply completely to the UK; Nevertheless, Williams (1980) writes: "The plutonium-producing natural uranium reactor cooled by air at atmospheric pressure thus became possible, and two such reactors were thereupon built at Windscale to supply the military programme. The urgency of this programme meant that there was not enough time to equip these reactors with the means of converting their waste heat into useful power, but the Ministry of Supply's engineers and scientists and also ministers and officials had this prospect fully in mind from the beginning" (63). Similarly: "...but an increased military demand for plutonium in the autumn of 1952 encouraged the atomic energy organisation, ... to recommend to the government that this demand be met by a reactor ... optimised now for plutonium production and with electricity as a by-product" (64).

(The relevance of a feared shortfall in energy supplies is also noted by Williams: "The government were still thinking in 1957 in terms of a 40 million ton gap in coal availability by 1965 ... In addition, oil supplies had seemed to be at particular risk following the Suez crisis of the previous year" (65)).

Hence the first UK reactors were dedicated to military use; by 1957 Calder Hall was operating and supplying the grid - becoming "a logical bridging step between the plutonium-production reactors at Windscale and commercial power stations". By 1981 Hill (1981) could write "the link between civil nuclear power and weapons proliferation is not direct and ... a nation wishing to have a nuclear explosive device can find easier, and cheaper means to its attainment than through a power programme" (67). This echoes Greenwood et al (1980) "A state that had no nuclear power industry would not be expected to acquire nuclear power generation facilities for the sole purpose of obtaining weapons material, unless it wanted to conceal its intentions. But even if that were the object, it is by no means clear that concealment would be easier than constructing special facilities clandestinely" (68). They go on to point out that that material that would be available from a commercial reactor would not, anyway, be weapons-grade, unless that reactor was operated specifically to produce at that grade; in which case it would be sub-optimal from its commercial standpoint.

However, a commercial nuclear power industry provides scientific and technological training and development; in addition it provides strong arguments, on its own grounds, for establishment of enrichment and reprocessing facilities. (Indeed this feature of the industry has been noted as a major economic problem in that its growth becomes an inevitable and unpreventable feature. Once spent fuel is accumulated it is "wasteful" merely to store/dispose of it - which leads to reprocessing, the breeder and an expanding industry (69)). Krass et al (1983) argue that there are strong, (and increasingly dangerous), links: "Uranium enrichment has always played an important role in nuclear weapon proliferation" (70), and "Given existing trends, the risk of nuclear weapon proliferation through the uranium enrichment route is definitely increasing" (71). One reason they give for this is excess supply of enrichment facilities and a consequent increase in competition - which could lead to a relaxation of non proliferation safeguards. The detail is not of importance here; the point is the continuation, not only in the public mind but also in academic literature, of the connection between military and civil uses of nuclear power. Marshall's (1980a) confrontation of the problem is discussed in Chapter V (72).

The final risk relevant here is one which is discussed by Hirshleifer and Shapiro (1977). It is the risk of over optimism in formulating the investment appraisal. The result is that the cost benefit analysis becomes based on 'if all goes well' estimates, rather than on the mean of the expected range for each element. Clearly, over optimism will heavily bias the outcome, but Hirshleifer and Shapiro argue that it is comparatively straightforward to deal with this type of risk. The necessary correction is simply to use the mathematical expectation for each element in the analysis rather than the "optimistic belief".

In their 1981 Report on the CEGB the Monopolies and Mergers Commission criticised the estimates used by the CEGB in their investment appraisal on precisely these grounds, stating in the conclusions to Chapter 5 of the Report: "... a presentation of investment appraisal results which takes as its starting point the central estimate, rather than one which would require a highly favourable and unlikely combination of circumstances, is more likely to avoid the risk of unconscious appraisal optimism" (73).

The problem highlighted by the MMC was the method chosen by the CEGB to deal with uncertainty and risk in project appraisal. For some variables forecasts were made in a standard fashion, assuming that the range of possible outcomes was normally distributed. These forecasts were for "background variables" such as future fuel prices, or national income, which the CEGB took to be exogenous. ("The CEGB bases its medium term estimates of new generating plant requirements on annual central forecasts of future electricity demand adopted by the Electricity Council after an industry-wide forecasting exercise in which the CEGB participates" (74)).

However, there remained estimates of "technical parameters" including forecast costs and construction times; these were clearly not taken to be exogenous since a part of the Board's management activity was dedicated directly to affecting them. In the case of these variables the CEGB chose to use as estimates "targets which should be quite feasible to achieve under ideal circumstances" (75). The internal CEGB 1979-80 Development review (which the MMC quotes in para 5.94) accepts that these will be "best estimates ... (with) a considerable likelihood that they will not be achieved". The justification for using two different ways of catering for uncertainty over future events lies in the exogeneity or otherwise of those events. Fuel prices are assumed beyond the control of the CEGB; hence, the use of standard forecasting techniques and a normal distribution to deal with uncertainty. Construction times are the concern of the CEGB management and estimating a mean time with a distribution does not make sense and is not a logical extension of the approach for exogenous background variables. An additional CEGB concern derives directly from the "target" nature of the technical parameters. Using a best estimate for construction time provides an incentive for those actually involved in the construction to hit a difficult target and gives an indication that the planners are aiming for high levels of efficiency. Alternatively, extending the target period 'just in case' could easily become self-fulfilling.

The result is that the two different approaches are combined to give the overall "basic estimate". Given the way in which they are derived, it is clear that these are not central estimates. Nevertheless, the basic estimates can then be used for sensitivity analysis showing the effects of assuming outcomes for given variables different from the values which have generated the basic estimate. The MMC conclusion is that the basic estimates need to be adjusted so as to "present outcomes associated with the central estimates of all the relevant determining variables" (76) despite the CEGB arguments (above) against this. This would require "rational estimates of the most likely outcomes for the technical parameters", based on "careful analysis ... of past outcomes and ... a realistic assessment of the consequences of managerial initiative designed to improve performance" (77). Hence, the MMC recommendation is that technical parameters be subject to the same forecasting procedure as is used for the background variables; targets may then be used for management incentives to improve on the central estimates. The implication is that the significance of uncertainty can be better represented as sensitivity analysis based on a probability distribution around a central estimate, rather than one based on a mixture of central and 'if all goes well' estimates.

However, there is another side to the problem of optimism in the preparation of estimates. Another view of technological risk is that the length of time needed to accommodate this risk is crucial. Over optimism leads analysts to underestimate development problems and this is shown in the AGR programme. Hence the MMC (1981): "It would appear that the origin of the delays and the cost increases was the euphoria induced by the apparent success of the Magnox stations at the time when an AGR programme was being conceived. This led to an underestimation of the problems associated with such technological developments as increasing gas temperatures from 450°C to 650°C and gas pressures by 100 per cent compared with early Magnox stations and, most important, leaping straight from the small 40MW Windscale AGR to the 660MW commercial AGR ... less than adequate design work and testing was carried out ..." (78). This highlights a further risk - if the technology fails or takes longer than anticipated to come on stream, society is forced to rely on alternatives which are themselves costly, while simultaneously paying increasing sums to get the mistakes corrected.

There is also the question of being too pessimistic and not undertaking developments because it is assumed problems will never be overcome. Thus in House of Commons (1981): "Difficulties being experienced with the present AGR programme derived from decisions made some fifteen years ago in the mid-1960s and a great many lessons have been learnt from this and subsequent experiences are being incorporated in current work on design and in the proposed methods of ordering and controlling construction" (79). This makes it requisite to consider not merely the short or medium term, (during which technological problems and risks will inevitably be significant), but also the longer term. If this is done then the risks diminish since there is the time to research into them and the money, since the full commercial benefits of the project will by then have been felt. Again from House of Commons (1981): "In the Board's experience new plant, whether nuclear or conventional, normally gives rise to problems which take a number of years to resolve"; and: "installation of new nuclear plant gives a net benefit; that is to say it is economic on energy cost saving alone" (80).

NOTES TO CHAPTER IV

(1) Bierman and Smidt (1980) p.34

(2) Ibid p.34

(3) Sugden & Williams (1978) p.64

(4) see Mackerron (1982)

(5) Baumol (1977) p.172

(6) McKean and Moore (1972) p.166
The U.K. has over 20 million income tax payers - see Social Trends 16 (1986)

(7) Arrow and Lind (1970) p.376

(8) Haveman (1977) pp.369 and 370

(9) Sandmo (1972) p.287

(10) Ibid p.300

(11) see Marglin (1963 a and b)

(12) This is not so in the isolation paradox. There, the individual given the assurance nevertheless chooses to do A.

(13) and/or wealth

(14) Warr and Wright (1981) p.144

(15) Mishan (1982a) p.247

(16) Ibid p.247

(17) Pearce (1977) p.360

(18) Freeman (1977) p.376

(19) CEGB (1984/5) Annual Report p.13 para.38

(20) Pearce (1977) p.363

(21) The Sizewell 'B' Inquiry was concluded on 7.3.85

(22) Jenkin (1982) p.38

(23) Pearce (1979) p.67

(24) Haveman (1977) p.371

(25) Arrow and Fisher (1974) p.319

(26) Pearce (1979) p.68

(27) CEGB (1984/5) p.30

(28) Pearce (1977) p.364

(29) Krutilla and Fisher (1975) p.73

(30) Jones (1980) pp.149-150

(31) Department of Energy (1977) Paper 39 para.172

(32) Krutilla and Fisher (1975) p.73

(33) see House of Commons (1981)

(34) Department of Energy (1976) para.49

(35) Ibid (1976) para.128

(36) Central Policy Review Staff (1976) para.3 p.VII

(37) Ibid para.4 p.VIII

(38) Ibid para.30 p.87

(39) quoted in Jones (1984)

(40) Solow (1974) p.30

(41) Weinberg (1972) p.28

(42) Ibid p.31

(43) Ibid p.33

(44) Ibid p.34

(45) Roberts (1984a) p.91

(46) Roberts (1984b)

(47) Weinberg (1972) p.34

(48) Roberts (1984a) p.108; 119

(49) Starr (1982) p.250

(50) Roberts (1984a) p.115

(51) OECD (1982) quoted in ATOM 311 September 1982

(52) MMC (1981) para.5.125

(53) Rasmussen (1975)

(54) Roberts (1984a) p.75

(55) Ibid p.77; 83

(56) Fischhoff et al (1981) p.165

(57) Coppock (1981) p.208

(58) Rothschild (1978) p.715

(59) Thomas and Otway (1980) p.130

(60) Ibid p.130

(61) Otway et al (1978) p.110

(62) Lonnroth and Walker (1979) p.11

(63) Williams (1980) p.35

(64) Ibid p.38

(65) Ibid p.64

(66) Ibid p.38

(67) Hill (1981) p.67

(68) Greenwood et al (1980) p.110

(69) see Widdicombe (1980)

(70) Krass et al (1983) p.41

(71) Ibid p.40

(72) In the Nuclear Energy Policy Study Group (1981) the proliferation problem was viewed as the chief obstacle to the use of nuclear power as an energy source. However, Ramsey (1979) argues that the connection between the nuclear industry and proliferation is very speculative so he does not attempt to include it in his quantification of unpaid costs.

Maxey (1979) argues that the real problem is to devise international safeguards against all weapons, their particular type being of less significance.

(73) MMC (1981) para.5.165

(74) House of Commons (1981) CEGB Memorandum M17

(75) MMC (1981) para.5.94

(76) Ibid para.5.161

(77) Ibid para.5.162

(78) Ibid para.12.78

(79) House of Commons (1981) CEGB Memorandum M17 para.15

(80) Ibid paras.28 and 24

CHAPTER V

THE ECONOMICS OF THE NUCLEAR FUEL CYCLE

V.1 INTRODUCTION

In this chapter the major elements of the nuclear fuel cycle are identified and considered in the light of actual cost estimates by the industry and economists; and of their general significance in terms of overall energy policy; and the growth and development of nuclear power.

The UK, USA and USSR have been using nuclear power to produce electricity commercially since the 1950s (then with prototype reactors). The first full sized reactors to come on stream in the UK were the Magnox reactors developed and built in the late 1950s and early 1960s. Similar reactors were built in France, while developments in Canada and in the USA produced alternative commercial designs. The 1950s was also the decade in which the American "Atoms for Peace" programme initiated the worldwide dissemination of information on nuclear power technology. By the end of 1978 there were some 220 reactors operating worldwide with a total capacity of some 120 GW (1) an energy equivalent of 3 million barrels of oil/day, or roughly 2% of world energy consumption. For the USA nuclear power was then providing some 13% of electricity; in the UK some 14%; Belgium 20% (2). France had the most ambitious target of all of meeting 20% of her energy needs by 1985, requiring nuclear power to provide some 50% of total electricity production (3). The 1981 Report of the International Atomic Energy Agency showed that by end 1980 the number of reactors worldwide had risen to 253, generating some 8% of world electricity. In addition, a further 230 reactors were then under construction and 118 were at the planning/ordering stage.

By the end of 1984 there were 318 nuclear power plants operating worldwide in 26 countries; they represented a capacity of over 206,000 MWe (4). French nuclear capacity had risen to 33,000 MW and nuclear plant accounted for nearly 60% of French electricity production (compared with 48% in 1983) giving France the highest percentage of electricity produced by nuclear power in the world (5). European nuclear capacity was over 65,000 MW (6). By the end of 1985 world nuclear capacity was over 240,000 MW (7) and in the OECD countries there were some 265 reactors in operation, providing about 20% of power. At that time the OECD was expecting capacity to double by 2000 (8).

Because the energy available from uranium is so great in comparison to that from fossil fuels, a substantially more complex fuel cycle and more elaborate capital infrastructure are made economically feasible. Although the output of electricity is by no means the only role suggested for nuclear reactors, it is their only current commercial use; a recent proposition for Magnox reactors has been to use the high temperature steam (350° C at 2500 psi) they can provide to recover heavy oil or bitumen at depths of 1500 to 3000 feet. There is a claimed conversion efficiency (measured as the calorific value of heavy oil produced to the energy value of steam production and injection) of 300% (9). The Swedish company ASEA - Atom devised a reactor project named SECURE (the Safe and Environmentally Clean Urban Reactor) to produce hot water for district heating. This aimed to provide 400 MW of heat at an outlet temperature of 110° C to cater for a community of 50,000. The USSR fast reactor BN 350 at Shevchenko on the Caspian Sea is designed to purify 120,000 tons of water a day as well as generating 150 MWe of electricity (10).

Thus electricity output is one element in an entire cycle of operations concerning nuclear fuel, and resulting in a worldwide industry. Conventionally the nuclear fuel cycle is divided into front end and back end activities. The front end of the cycle relates to the mining and milling of uranium ore to produce "yellowcake" (80% pure uranium oxide (U_3O_8)), the purification of the yellowcake and conversion to uranium hexafluoride gas; the enrichment of this gas, production of uranium dioxide and fuel fabrication. The back end of the fuel cycle concerns the methods of dealing with the irradiated fuel rods once they leave the reactor. These involve spent fuel storage, reprocessing and waste solidification and disposal. The possibility of reprocessing the fuel makes it necessary to divide the back end of the cycle further into either an open or a closed cycle: the open or "once-through" fuel cycle eliminates the reprocessing option and is concerned with the processes necessary to store safely and indefinitely the spent fuel and accumulated waste products. The closed cycle still involves the storage of waste, but includes the reprocessing of the spent fuel to extract energy-rich components which it still contains and which may then be recycled to the reactors.

V.2 MINING AND MILLING OF URANIUM ORE

Mining of uranium-bearing rock initiates the nuclear fuel cycle. Uranium is a mineral which occurs naturally in ore in varying levels of concentration; the generally higher grade ores currently mined have uranium concentrations in the region of 0.1% up to 0.5% by weight. In order to obtain (after refining) 150 tonnes of natural uranium, the requirement would involve mining, at the most, some 300,000 tonnes of ore (11). Such a quantity of natural uranium burnt in a reactor for one year would generate as much electricity as would a coal fired station burning over two million tonnes of coal. The nuclear plant would not require the mining of an equivalent tonnage of ore until the average uranium oxide content of the ore fell to a range of 0.006% to 0.007%, which is some twenty times lower than the current average (12). This comparison of relative mining tonnages also leads to comparison of land areas devoted to nuclear and coal fired plant. A 1000 MWe nuclear plant would represent annually mining of some 20 to 50 acres of land (at an ore concentration of 0.2%) plus a further 30 to 70 acres to accommodate milling plant and storage of residue (tailings). The equivalent output coal plant would require 100 to 400 acres of mining land plus space to dispose of ash and sludge (although some of this land can be reclaimed when mining and waste dumping is completed) (13).

Naturally, as mining continues the more accessible and richer ore reserves will be depleted, leading to increased mining costs as greater volumes of rock will have to be processed to achieve given outputs of uranium oxide. (Where open cast mines are in operation the possibilities for very large scale activities are offered, but the more intensive mining could impose significant and expensive environmental problems).

Once mined the ore yields its uranium content in the milling processes. The rock must be crushed and ground, and from the slurry that is formed a purified uranium salt known as "yellowcake" is separated. This powder will contain some 80% uranium oxide (U_3O_8).

The OECD has published a series of reports on world uranium potential compiled in a joint study by OECD, NEA and IAEA. (14). These estimates of resource availability are necessarily dependent on the cost allowed for exploitation. Should the price of a mineral rise then reserves previously untouchable as too expensive become desirable. Thus 'Reasonably Assured Resources' refers to the expectations of what will be recoverable from known deposits using existing technology at current prices. Estimated Additional Resources refers to predictions that deposits will be discoverable and exploitable at current prices within as yet unexplored areas either of known deposits or of probable ore-bearing rock (15).

Despite their limitations as measures of any absolute availability, these estimates serve to give some guide as to the tightness or otherwise of supply over time, and thus to the need for continued exploration to meet the industry's desired position of having exploration lead production by a decade. The rate of exploitation itself will be directly related to the rate of change of the market price net of extraction cost. Should this be rising at a rate less than the available interest rate it will pay mine operators to deplete reserves as fast as possible; similarly a net price whose rise is at a rate greater than the interest rate will encourage a decrease in exploitation of a resource which now offers a better return than the money market (16).

A recent claim holds that on current evidence not much more than 100,000 tonnes of uranium could be retrieved annually from known reserves, and while active exploration could increase this, there remains a lead time of ten to fifteen years between prospecting and bringing a mine on stream; the fall in the spot market price from

$115/kg in 1979 to $66/kg in 1981 would not have been an encouragement to such investment (17).

Kroch (1980) suggests that a typical mine processing some 1,000 tonnes of uranium ore per day would represent capital costs in the range $10 million to $20 million with operating costs of some $1.10 per kilo of U_3O_8 ($ 1974).

Given the evident dependence of the largely private enterprise mining and milling industry on the final demand for uranium in electric power stations, it is clear that any uncertainty in orders for and development of these stations can result in substantial problems for the industry which will lead to a reduction in the flexibility of output. Uranium exploration is more costly than is the case for oil; it is expensive to close and reopen mines, and the time lag between exploration and mine operation may be up to eight or ten years. Similarly the electric power generating industry suffers greatly in periods of uncertainty; planners must operate on the construction time for a reactor being at least ten years and the plant having an expected lifetime of over thirty years. Since in general electricity producers are required to meet demands placed on them, stability of fuel supplies becomes a highly significant element in the decision process.

By 1980 a uranium glut was becoming apparent, showing itself in falling prices, mine closures and cancellations of future mine projects. Since it can cost more to reopen a closed mine than to start afresh, a prolonged weak market for uranium would reduce the chances of mines being reopened and further limit the responsiveness of output.

What little elasticity of supply there is in the short term at this point in the cycle is provided either by stocks or by increasing the recovery rate of U_3O_8 in the mill by leaching more oxide from what would otherwise be the waste; the latter will inevitably lead to increased costs. Should the nuclear fuel cycle be closed, however, the reprocessing of irradiated fuel rods will generate more fuel for recycle to reactors, thus alleviating to some extent the pressure on the mining and milling sector; furthermore the introduction on a commercial scale, of breeder reactors burning plutonium would expand the timescale of usefulness of existing stocks of uranium dramatically. Lellouche (1980) quoting Andre Giraud, then head of the Commissariat a` l'Energie Atomique: "France owns estimated natural uranium reserves of 100,000 tonnes ... consumed in Light Water Reactors they represent 800 Mtoe or one third of the North Sea Oil reserves. Through the use of breeder reactors this uranium can produce 50,000 Mtoe, the equivalent of all the Middle East Oil reserves".

Thus IIASA (18), argues that 2030 would be the date of exhaustion of even the most optimistic resource estimates (excepting very dilute uranium sources) if consumed in a once through cycle, so that uranium resource estimates serve to define the period of useful life of existing reactors systems and to indicate the proximity of a move toward commercial breeder reactors. "The 'once through cycle' ... a sensible alternative for a country rich in uranium but not for countries lacking such resources" (19).

Unusually for such a commodity there is no international exchange nor any "marker" price for uranium, although private organisations do attempt to publish up to date contract prices. In 1972 the Uranium Marketing Research Organisation (UMRO) was formed amongst companies and governments, outside the USA, concerned with uranium mining. This organisation existed to exert pressure to raise prices, an event which, by 1975, had occurred to an extent sufficient for UMRO to cease to exist, (although prices have since fallen again, and both USA and Canada initiated legal action against UMRO).

Uranium mining and milling is an industry comprising a comparatively small number of companies exploiting reserves which are (currently) fairly highly concentrated geographically. It is by no means easy for new entrants to gain access to such an industry, whose output is a commodity without direct substitute. Given these conditions a cartel might seem a highly probable outcome; nevertheless, Buckley et al (1980) argue that any further moves toward a cartel are unlikely for two reasons. Producers would be unwilling to be the cause of similar economic problems to those resulting from the OPEC cartel (although given the degree of difference between the uses served by oil and the sheer volumes of output this argument seems rather weak). Secondly any oligopolistic behaviour would be counteracted by vertical integration from the large users in the private sector whose unique dependence on uranium would otherwise leave them facing ever higher prices. In France, such vertical integration already exists as CEA through its subsidiary COGEMA (20) has gained control with a legal monopoly over the entire commercial services of the fuel cycle from uranium mining to enrichment and reprocessing (21). In 1978 the first uranium was produced from the mine owned by Cominak (La Compagne Minière d'Akouta) in Niger, with a target full capacity of 2,000 tonnes per year by 1980. CEA holds shares in Cominak, together with ENUSA (Spain), OURD (Japan) and the Niger government (22).

V.3 CONVERSION - ENRICHMENT AND FUEL FABRICATION

The next stage in the front end of the nuclear fuel cycle involves the purification of yellowcake and subsequent manufacture into fuel for the reactors whose types vary throughout the world. The most widely used is the light water reactor (LWR) which includes both Pressurised water reactors (PWR) and Boiling water reactors (BWR), developed in the USA in a manufacturing industry dominated by Westinghouse and General Electric. Both the UK and France developed gas cooled graphite reactors (the UK Magnox reactor) but these have been superceded in the UK by the indigenous Advanced Gas Cooled Reactor (together with current CEGB plans for a third phase of reactors based on the Westinghouse PWR design), and in France by the PWR whose monopoly supplier is Framatome under licence from the American company Westinghouse. In the mid-70s CEA became a shareholder in Framatome, and Westinghouse agreed to a gradual decrease in its own participation (23). In Germany the largely privately owned industry is based on a reactor type derived from the basic Westinghouse model; by the end of 1978 there were 25 nuclear power plants in operation or under construction in Germany of which 21 were the responsibility of one company, Kraftwerk Union, which had also built the nine reactors exported from Germany with orders from Spain, Switzerland, the Netherlands and Austria (24). At the end of 1984 F.R. Germany had 19 nuclear plants operating to produce 24% of total electricity (and eight more plants either planned or under construction) (25).

The Canadian development of nuclear power has led to a unique design of heavy water reactor known as CANDU which has found some export markets in Argentina, India, South Korea and Pakistan (26). At the end of 1978 twenty-two countries were operating a total of 223 power reactors with an average size of over 800 MWe (27).

The fundamental process on which all of these rely is the chain reaction of fission in nuclei of uranium. Natural uranium consists of two isotopes; 99.3% of it is made up of ^{238}U, the remaining 0.7% is ^{235}U (the numbers 238 and 235 refer to the weight of the atomic nucleus; thus the two isotopes differ in their weights but not in their chemical properties). The isotope ^{235}U is said to be unstable as spontaneous fission may occur. The nucleus of the atom breaks up and this will cause excess neutrons (which form part of the nucleus) to be emitted at high speed. If one of these neutrons should be absorbed by the nucleus of another atom of ^{235}U, the second nucleus becomes 'excited' and so unstable that it too will undergo fission, again throwing off excess neutrons, and releasing energy in the form of heat. If it were possible to arrange for this process to be continued, then there would be a chain reaction with an output of heat; if, however, the excess neutron collides instead with a nucleus of ^{238}U then it will simply be absorbed and there will be no new fission and thus no chain reaction would occur.

Evidently the engineering objective is to design a nuclear reactor such that a continuous chain reaction is possible. The condition of this chain reaction should be such that one of the neutrons emitted in each fission should go on to cause a further fission and allow the chain reaction to repeat. Should more than one neutron cause additional fissions, the chain reaction would grow exponentially; and similarly it could decline.

However, natural uranium contains the relatively low concentration of 0.7% of the fissile ^{235}U, and this necessitates the introduction of a mechanism to slow down - or "moderate" - the emitted neutrons, and by so doing increase the probability that a neutron will be absorbed by a nucleus of ^{235}U which will undergo fission and so allow the continuation of the chain reaction. (Natural and low-enriched uranium contains a low concentration of the fissile material, the effect of the moderator in slowing the neutrons is to increase the probability of a chain reaction by increasing the fission cross section or apparent size of the nucleus as seen by the incident neutron). Thus light water reactors (PWR and BWR) are moderated by ordinary (light) water; the British Magnox and AGR use graphite and the CANDU uses heavy water (deuterium oxide). Once the reaction is made possible (by bringing together a sufficient quantity of uranium fuel) control over start-up and shut-down is exerted by withdrawal and insertion of control rods. These are made of substance which has the property of absorbing neutrons: when the rods are inserted into the core of fuel in the reactor they will act to prevent emitted neutrons from causing further fission; as they are removed so the chain reaction may begin again. Boron is an ideal substance for manufacture into control rods. (Further safety and control devices are part of the engineering design).

Finally, a means must be found to draw off the heat generated and drive the turbines. The PWR uses light water under high pressure to act as both the moderator and the coolant; the Magnox and AGR use carbon dioxide gas to cool the fuel and transfer the heat. Each of these reactors uses a secondary water circuit heated by the water or gas to generate steam for the turbines. (The BWR uses the steam produced in the process of cooling the reactor, and does not require a secondary circuit).

Thus these "variations on a theme" (collectively grouped as "thermal" reactors, since slow neutrons are also known as thermal neutrons) rely on the instability of the ^{235}U isotope, with neutrons slowed by a moderator. And in the cases of the British Magnox and Canadian CANDU reactors the fuel input is pure natural uranium. However, the other reactors mentioned so far operate on fuel in which the naturally occurring ratio of ^{235}U has been increased - fuel which is enriched so that its concentration of ^{235}U is between 2.0% and 3.0%. (Even this concentration is still low enough to require a moderator to slow the neutrons to ensure the chain reaction). The major benefit of enriching the fuel input to this level is that the reactors can operate with a substantially lower fuel load and thus smaller core size than is required by CANDU and Magnox. Fuel enrichment means that both higher rating (measured as MW/tonne) and higher burnup (MWdays/tonne) are achieved; the smaller core size is made possible as each fuel element is contributing a greater energy output. The cost lies in the economics of the enrichment process.

V.3.1 Enrichment

To produce fuel for reactors operating on enriched uranium, the purified natural uranium is converted to uranium hexafluoride gas (UF_6, known as 'Hex') which is a suitable form for handling. The Hex is then transported to the enrichment plant. There are enrichment plants in the USA, UK, France, FRG, the Netherlands and South Africa, operating one of three methods: gaseous diffusion, gas centrifuge, or the nozzle process.

The work performed in the enrichment plant is measured in Separative Work Units (SWU) and defined in kilograms, the capacity of the entire plant being defined in SWU per year. Since the object of the process is to produce enriched uranium, a by-product is uranium depleted in ^{235}U, known as the "tails". The "tails assay" refers to the ^{235}U which is allowed to remain in the stream of depleted tailings. Thus, operating the plant with a tails assay of 0.3% means that there will be 0.3% ^{235}U and 99.7% ^{238}U in the residue remaining to be stored. This high concentration of ^{238}U renders the tails stream useless as a fuel within the framework of the nuclear fuel cycle presented so far; but should the fast reactor become a commercial proposition, this inventory of depleted uranium will take on enormous importance.

The differing possible combinations of the various elements of the enrichment process may now be seen. A given quantity of enriched uranium may be obtained by simultaneously lowering both the tails assay and the original input of natural uranium feed; the reduced tails assay will imply more SWU per kilogram of product, but this increase in cost may be traded off against the smaller expenditure on uranium. Buckley et al (1980) point out that reducing the tails assay from 0.3% to 0.2% reduces the natural uranium required by 18%, and Gordon and Baughman (1979) show comparisons for the case of the typical American LWR using "fuel enriched to 3%, the requirement would be 3.425 SWU/kg of product with a tails assay of 0.3% or 4.306 SWU/kg of product if the tails assay is 0.2%" (28). Similarly reducing the tails assay with a given input of natural uranium feed will raise the enriched output quantity. There will thus be some optimum tails assay which will vary with the price of natural uranium and with the price of energy used in the enrichment plant.

The original process (whose origins lie in nuclear weapon development and which is still to some extent secret), is gaseous diffusion. US Department of Energy plants operate at Oak Ridge Tennessee, Paduca Kentucky, Portsmouth Ohio; the USSR operates this process, as does France through the Eurodif plant at Tricastin which began production in early 1979, with a maximum output of 10.8 million SWU (29). In the gaseous diffusion process Hex is pumped through a porous membrane more than one thousand times to obtain product enriched to 3%. The ^{238}U atoms are marginally denser than the ^{235}U atoms, and so are just slower to move through the membrane. Thus as it is pumped through the cascade of barriers, the Hex becomes very slightly enriched at each. The energy requirements for this process are substantial as there must be so many repetitions.

The second major enrichment process is the gas centrifuge method. In March 1970 Britain, the Netherlands and West Germany signed the "Almelo Treaty" which was an agreement to pool their research and development programmes in uranium enrichment. The joint sales organisation is URENCO and the two gas centrifuge enrichment plants now operating are at Almelo in the Netherlands and Capenhurst UK, (operated by British Nuclear Fuels Ltd. - BNFL - who also operated a diffusion plant at Capenhurst. This produced enriched uranium for the AGRs and recycled uranium recovered from the Magnox reactors, enriching it to natural ^{235}U concentration, but has now been closed). There is a further enrichment plant in Gronau in F.R. Germany to accommodate the F.R. German electricity companies' requirements for an independent source of enrichment capacity (30).

The gas centrifuge spins the Hex and causes the heavier ^{238}U atoms to move outwards faster than the ^{235}U thus achieving the desired separation. Enrichment to 3% takes some twelve repetitions and only about 10% of the power requirement of the gaseous diffusion method (31), although Eden et al (1981) quote figures of 2500 KWh of electricity per SWU for a gaseous diffusion plant compared to 100KWh for a gas centrifuge. A further benefit of the gas centrifuge is that small additions to capacity can be made economically, a desirable property when there is no firm commitment to permit expenditure on a substantial development; it appears that the maximum size required to achieve all available economies of scale is approximately one third of that needed for a gaseous diffusion plant. Kroch (1980) quotes the optimum scale of a diffusion plant to be 9 million SWU. Against this, however, must be set the drawback that the great stresses on the centrifuges make them very expensive both to manufacture and to replace.

URENCO claims (32) that alone with Eurodif it offers a commercial enrichment facility; their argument is that the USA with more than 60% of world enrichment capacity quotes prices which barely cover energy costs and that the USSR (with 7% of world capacity) simply sets its prices 5% below those of the USA. The Soviet Union has been supplying enriched uranium to West European countries (particularly F.R. Germany) since 1974; in 1980 $43.8 million worth of Soviet enriched uranium was imported into the United States, some to be fabricated into fuel for re-export to F.R. Germany, some for use in US power stations (33). The capacity shares of Eurodif and URENCO are 25% and 5% respectively. By the middle of 1980 a succession of cancellations and cuts worldwide in orders for nuclear power stations had led to a position of substantial over-capacity in the enrichment industry.

The 1976 US charge for a fixed amount of enrichment was $61 per SWU (34). The Gordon and Baughman model (1979) estimates a government charge of $75 per SWU ($ 1975) until 1990. This matches Kroch's (1980) estimate of ($ 1974) costs for a diffusion plant. Prior (1979), however, puts enrichment costs at about $110 to $120 per SWU, arguing that costs have risen as the process has become increasingly commercial (and correspondingly less militarily based), thus explaining in large part the CEGB evidence that fuel for nuclear plant increased by more than 22% annually 1968 to 1978. In the UK context Prior gives the breakdown of costs as: mining and milling 33%; conversion 1%; enrichment 30%; fuel fabrication 9%; reprocessing 25%; reconversion 1%; high level waste storage 1%; this is for a mid-1978 fuel cost of some £0.35 GJ.

This is in contrast with Greenwood et al (1980) who state that the overall significance of the costs of enrichment as part of a nuclear power programme is relatively small, at about 5% of the total cost of generating power.

The IIASA study (35) estimates that an enrichment plant with the capacity to provide for forty LWRs can be built in the same time as a LWR at four or five times the LWR construction cost. Their worldwide total for enrichment capacity (outside centrally planned economies) at the end of 1978 is just under 24 million SWU per year. A 1000 MWe LWR at a 65% load factor would need approximately 100,000 SWU per year of enrichment service (36).

The third enrichment process currently operating commercially is the aerodynamic technique developed by UCOR in South Africa. This is of a type similar to that invented in Germany by Becker, and involves mixing Hex with either helium or hydrogen, compressing this and pumping it over a curved surface where it is separated by a knife edge. The power requirements for this process are substantially greater than for the gaseous diffusion method (some 50% per SWU more), although it is a simpler technology. It has proved acceptable enough for Brazil to have purchased it as part of her nuclear development programme, since she has substantial hydroelectric resources at distances from population centres that are too great to make it worthwhile transmitting electricity from them (37).

The fourth alternative is laser enrichment, which has been demonstrated in laboratory experiment, and is predicted (38) to be a probable commercial technique in the 1980s. The expected benefits of the technique (which involves exciting by laser only ^{235}U or ^{235}U hexafluoride atoms so that they may be separated from the ^{238}U) are that the power consumption should be comparatively low and the degree of separation in a single stage very high. Not only might virtually total separation be feasible, but the tails from previous enrichment processes would become suitable inputs to laser enrichment, which would thus represent a means of stretching uranium supplies.

V.3.2 Fuel Fabrication

Following enrichment the enriched Hex is transported to the fuel fabrication plant in which the particular manufacturing process depends on the type of reactor to be fuelled. At BNFL's plant at Springfield the Hex is converted to small ceramic pellets of uranium dioxide (UO_2) and sealed into stainles steel AGR fuel rods. By the end of the 1970s the Springfield factory was producing some 2,000 tonnes of nuclear fuel a year, with a target of 5,000 tonnes by 1990 (39). The plant is also to use Westinghouse technology to fabricate the fuel assemblies should the CEGB's PWR programme go ahead (40). The Springfield plant also exports Hex, powdered pellets and finished fuel, particularly to France, Italy and Japan (41). In the process for fuel manufacture for LWRs the pellets of UO_2 are loaded into Zircaloy fuel rods. Kroch (1980) estimates an operating cost of $70 per kilogram of uranium, Gordon and Baughman (1979) cite a range of estimated fabrication costs from $70 to $150 ($ 1975).

V.4 BURNUP

The fuel rods are now ready to be inserted into the reactor where they are "burned" in the core over three to five years. The chain reaction of fission is now allowed to take place to generate power; in addition fission products will appear and begin to build up in the fuel. These products have neutron-absorbing properties and will thus inhibit the carefully balanced chain reaction until a point is reached where that reaction is no longer able to be sustained by the fuel which must then be replaced. The actual procedure for reloading the reactor varies according to type - some need to be shut down completely, others, such as the AGR, are designed so that they may be reloaded while still on stream.

The period of core life and average core burnup (measured in megawatt days per tonne uranium) at the end of the life of the fuel rods will vary with reactor and with the position of the fuel rod within the core. Thus the BWR has a lower burnup per tonne uranium than the PWR. A representative PWR burnup would be 33 thermal megawatt-days per kilogram at 33% thermal efficiency (42). The AGR has a rating and burnup which are both lower than those of the LWR, but its higher thermal efficiency (or Carnot efficiency), demonstrated by the high temperature heat it provides is compensation for these deficiencies. Although there is little to choose in the amounts of natural uranium consumed by thermal reactors, the Magnox reactors using pure uranium have comparatively low burnup due to their relative ^{235}U poverty, and graphite moderator. The use of heavy water as moderator and coolant in the CANDU allows a substantially higher fuel utilisaation (as heavy water does not absorb as many neutrons as does light water), although the cost of heavy water detracts from this benefit. Similarly fuel pins placed in core positions with higher neutron flux and power densities will need to be replaced earlier than others.

Prior to their insertion into the reactor the fuel rods do not present any radiation risk and they may be safely handled without the use of any shielding. Having undergone burnup in the reactor, however, they emerge emitting intense radioactivity and heat. Shielding becomes vital and the used rods are transferred immediately to cooling ponds. These are large metal lined concrete pools of water which will allow the heat to dissipate from the rods, and will present a satisfactory storage area for the period of more than one year necessary to allow the initially very intense radiation to decay to a level where the rods may undergo further processing.

Although no longer useful in the reactor core, the rods contain 97% uranium; this is almost entirely ^{238}U but there will also still be some ^{235}U (the actual quantities of the various constituents of the spent fuel rod will depend on the reactor being used). In addition some of the atoms of ^{238}U will have absorbed neutrons; this produces ^{239}U which decays and becomes plutonium (^{239}Pu).

Thus all reactors produce plutonium, in varying quantities, and as it is a fissile material it contributes to the power output by sustaining the reaction. The yield of plutonium in tonnes per year from a 1,000 MWe station operating continuously would be:

AGR	0.25	
PWR	0.33	
CANDU	0.51	
Magnox	0.75	(43)

V.5 REPROCESSING

The uranium and plutonium represent an immense source of still untapped energy. Whether or not this energy is to be used depends on the decision concerning the nuclear fuel cycle. If the cycle is to be left open, then the contents of the fuel rods must be dealt with to allow indefinite safe storage. Alternatively the cycle may be closed and in this case the fuel rods will be reprocessed to separate out the energy rich materials so that they may be recycled. The decision revolves around the balance to be struck between the extra costs involved in reprocessing (against the comparatively small cost of indefinite storage) relative to the benefits of the availability of depleted uranium and plutonium which will fuel a fast reactor. The value of the uranium is determined by the mining, conversion and enrichment costs; the value of plutonium must reflect these as well as additional costs caused by increased safeguards that are needed.

If spent fuel is reprocessed then the result will be stocks of ^{238}U, ^{235}U, plutonium and fission products and actinides which are waste and must be dealt with as such; (actinides are heavy elements with atomic weights above actinium and include thorium, plutonium, uranium, americium and curium. They are created when uranium or another heavy element absorbs neutrons). For example, irradiated Magnox fuel contains more than 99% depleted uranium, 0.27% plutonium and 0.4% of other actinides and fission products (44) while the figures for AGR or LWR fuel are 97% uranium (which is still slightly enriched in ^{235}U) up to 1% plutonium and 2 to 3% fission products and actinides (45). For every tonne of uranium that enters the LWR (enriched to 3.3% ^{235}U), 24 kilos of ^{238}U and 25 kilos of ^{235}U are consumed; that is converted to 35 kilos of fission products, 8.9 kilos of isotopes of plutonium, 4.6 kilos of uranium 226, 0.5 kilos of neptunium 237, 0.12 kilos of americium 243 and 0.04 kilos of curium 244. The remainder is unburned uranium containing 0.8% ^{235}U (46). The figures for fission products and transuranic elements (those elements with atomic weight above uranium) will be increased by longer burnup. On exit from the reactor this tonne of material will be emitting 300 million curies of activity and 3,300 kilowatts of heat, (the latter reducing to 1 kilowatt after ten years). The UK has been reprocessing fuel from Magnox reactors for some years at Windscale (Sellafield) and the result of the 1977/78 Windscale Inquiry was to accept the BNFL plan to construct the thermal oxide reprocessing plant (THORP) to reprocess the oxide fuel from the AGR.

The French reprocessing capability is based on Cogéma's plant at La Hague and was planned to be 650 tonnes of LWR by 1984, and eventually 800 tonnes, which is the initial capacity intended for the new plant. 1984 was also the planned date for the Traitement Oxydes Rapide plant to be built at Marcoule to reprocess the spent fuel from the Phoenix reactor (47). Cogéma has, since 1977/78, entered reprocessing contracts with F.R. Germany, Japan, Austria, Belgium, the Netherlands, Sweden and Switzerland (48).

The German reprocessing developments were based on the formation of the "Deutsche Gesellschaft für die Wideraufarbeitung von Kernbrennstoffen" (DWK) which built a small scale prototype facility at Karlsruhe. The full size plant planned for Gorleben was to take a throughput of 1400 tonnes of spent fuel giving an output of 14 tonnes of plutonium per year. The objective of this development was to create an integrated waste management centre, as it was also intended to use the site for the construction of plant to manufacture mixed oxide fuel elements, and to deposit high level waste permanently in salt rock caves deep underground. The whole project went into abeyance waiting for approval from Lower Saxony (49).

USA reprocessing at West Valley and Hanford has been halted since April 1977 when President Carter called for an investigation into the significance of the "plutonium economy", with the initiation of the International Fuel Cycle Evaluation (1980) (the civil plant at West Valley had reprocessed 630 tonnes of spent fuel between 1966 and 1972) (50).

It is argued (51) that a reprocessing plant only achieves economies of scale once it is capable of a throughput in excess of 1000 tonnes/year, which represents the output from a very large programme - perhaps reactors generating over 50,000 MWe. If so the export of reprocessing facilities becomes a significant part of the economics of such a plant. In the mid 1970s France exported small reprocessing plants at relatively low prices to Pakistan and South Korea, in contracts whose value was estimated at $200m and $10m, while reprocessing contracts at La Hague have earned some 12 billion francs ($2.5 billion) (52) and have avoided weakening the French market power in this field.

The optimum size for a reprocessing plant is given in Greenwood et al (1980) as 1500 tonnes per year with an estimated cost of between $500 and $800 million; operating costs will vary with throughput since there are economies of scale available. A range between $180 and $250 per kilogram of spent fuel is cited as an estimate for the costs of the back end of the fuel cycle, covering initial storage, transport, reprocessing, conversion and waste management. Since they also quote a range of $50 to $150 per kilogram as long term fuel storage costs, there is little to choose on this evidence alone between an open or a closed cycle. (A cost of $100 per kilogram is also quoted in Nuclear Energy Policy Study Group (1981) as the total cost of waste disposal, 1976). They conclude that the back end of the fuel cycle would represent up to 10% of the total fuel cycle costs, (and therefore only a few per cent of total electricity costs), again in contrast to Prior (1979).

Parker (1978), notes that any estimate for long term spent fuel storage costs must be speculative as no detailed work had been done on the alternatives. Using BNFL estimates of £225,000 per tonne for dry storage (in inert gas) and £150,000 per tonne for wet storage (in cooling ponds) Parker concludes that reprocessing is the desirable solution. The BNFL estimates for reprocessing are £260,000 per tonne (or £200,000 after allowance is made for the recovered uranium, valued in the report at $30 per pound) which makes it immediately preferable to dry storage, and, in fact to wet storage, since there are probably corrosion problems associated with spent AGR fuel. The size of reprocessing plant desired by BNFL does, at 1200 tonnes, conform to the above estimates of the optimum.

Having completed their term in the cooling ponds the fuel rods are transported to the reprocessing plants in containers designed to shield the radioactivity, to avoid excessive heat build-up and to remain intact in case of accident; in the UK the quality of the containers is established by the Department of Transport, based on overall safety considerations laid down by the Health and Safety Executive. After further cooling the fuel rods pass through a robot operated "decanning" plant which chops them up and strips away the outer cladding leaving the used fuel to be dissolved in nitric acid prior to further chemical treatment whose result is the separation and extraction of the uranium, plutonium and waste. Some of the uranium will be suitable for transport back to the enrichment plant as its ^{235}U content is sufficiently high to make economies in that process. The 1980 BNFL annual report stated that their Capenhurst diffusion plant was enriching to natural concentration the uranium recovered at Sellafield from spent Magnox Fuel, with a consequent reduction in the UK's requirement for uranium imports of several hundred tonnes per year. BNFL has undertaken an investment programme of more than £16m for the 1980s for the refurbishment and development of the Magnox fuel reprocessing plant which is currently working to deal with fuel from UK reactors as it is discharged. With additional Japanese and Italian Magnox reactor fuel BNFL anticipated a throughput of 900-1000 tonnes a year in the 1980s.

Remaining uranium will add to existing stocks of depleted uranium held at enrichment plants. (Now it no longer represents the handling problems of intense radioactivity that was the case prior to reprocessing).

A further point concerning the effect of reprocessing is that it reduces substantially the quantity of long-lived radioactivity in the remaining waste (by removing almost all of the plutonium which has a half life of 25,000 years). Other long-lived isotopes remain and do represent management and handling difficulties, although the volume and heat output of the waste resulting from the reprocessing operation are probably little different from those in the original spent fuel.

UK estimates of the amount of depleted uranium separated during the reprocessing of irradiated fuel elements are:

1977-78	850
1978-79	690
1979-80	750-800 tonnes uranium (UO_3)

plus some 2500 tonnes of uranium as magnox fuel and 100 tonnes uranium as oxide fuel in storage facilities either at the power stations or Sellafield (53).

The recovered plutonium could now be used together with recycled uranium as mixed oxide fuel in LWRs. Marshall (1980a) gives the overall fuel savings from this as:"recycle of uranium alone economises on the supply of uranium fuel by 23% and the recycle of plutonium saves up to an additional 16%". This is a comparatively small saving whose value will increase with any growth in the price of uranium ore. Similarly the Ford/Mitre study (54) argues that plutonium recycle in LWRs represents only a small economic benefit by lowering the fuel cycle cost by 10% and electricity costs by 2%.

V.6 FAST REACTORS

The alternative recycling solution is to develop fast reactors whose fissile material is ^{239}Pu, or perhaps a mixture of plutonium and ^{235}U, surrounded by ^{238}U. The relative concentration of plutonium to the uranium is 20:80; at this concentration the desired chain reaction in the plutonium will occur. In this case the speed of the neutrons is not moderated in any way (hence the name fast reactor); in addition the number of neutrons produced when an atom of plutonium splits is greater than was the case for ^{235}U fission in a thermal reactor. When these are absorbed by ^{238}U the result is the formation of more plutonium. Thus the operation of the fast reactor involves fission of plutonium generating the heat to drive the turbines, plus the conversion of some of the blanket of ^{238}U surrounding the core to plutonium. Because it behaves in this manner in the reactor, the ^{238}U is referred to as the fertile material.

Since the reactor not only 'burns' plutonium, but also generates more, it is also known as a breeder reactor. Thus the fast breeder reactor saves uranium over its lifetime by generating its own fissile material. The neutron flux in a fast reactor is much higher than in a thermal reactor and is sufficient both to provide heat and to convert ^{238}U simultaneously. The predicted uranium saving is substantial: "over the lifetime of each 1GWe of fast reactor capacity installed there will be a reduction of some 4000 tonnes of uranium compared with using a similar thermal reactor capacity" (55). The thermal reactors also makes use of the plutonium it produces but it can only operate with ^{239}Pu and the longer the fuel remains in the reactors the greater are the amounts of ^{240}Pu, ^{241}Pu and so on that are formed. These, however, represent fuel to the fast reactor which can consume them perfectly satisfactorily. The objective of the fast reactor design can be such that after a given period there will have been produced a surplus of plutonium, over and above the operating requirements of the reactor itself, sufficient to provide for another reactor; this period is known as the linear doubling time. The core of the fast reactor is compact yet produces great amounts of heat; this is no longer transferred by carbon dioxide, but by liquid sodium which has a number of desirable properties. It is very efficient in transferring heat without the prerequisite of being at high pressure and it does not interfere with the action of the fast neutrons since it is not a good moderator. The liquid sodium serving to cool the reactor core becomes radioactive; it transfers its heat to a secondary sodium circuit which is not radioactive and which finally heats water to steam for power. The major significance of the fast reactor, however, is not that it breeds plutonium (all thermal reactors do that). Current designs of LMFBR have a fuel doubling time of 25 to 30 years (56). This implies that the breeding gain (that part of the total fissile find produced in the reactor, over and above the quantity of primary fuel destroyed which is thus available for use in new plant) is not particularly high. The breeding gain will depend on (among other things) the losses in reprocessing, fuel design factors, rating and burn up. Thus provision of plutonium for them would need to rely on a continued thermal programme based on reactors having a high uranium to plutonium conversion ratio; the fast reactor has the capacity to produce a small surplus which can build to provide the inventory for a new reactor.

What the fast reactor also has to offer is an immensely greater ability to extract energy from its fuel input; while the thermal reactor can utilise some 1% of the energy in its fuel input, the fast reactor is able to make some 60% of the energy in the original uranium available. The significance of this is shown in the comparisons in Table V-1.

Table V-1 Comparative Energy Content of Fuels

	Specific energy content therms/ton	Annual fuel required for 1 GWe power station, 30% efficiency 70% load factor
Coal	230 - 300	2.3 m tonnes
Oil	420 - 440	1.5 m tonnes
Gas	500	
Uranium in thermal reactor	4,800 - 8,000	26 tonnes enriched uranium (=> 150 tonnes natural uranium)
Uranium in fast reactor	480,000	

Sources: Eden et al (1981), Hunt and Betteridge (1978)

The economic significance of this is further highlighted by the assertion that 1 tonne of depleted uranium from the reprocessing of Magnox fuel will, if fissioned in a fast reactor produce the same quantity of electricity as would be produced by burning 2.1 m tonnes of power station coal or 8 m barrels of oil (57); existing stockpiles of depleted uranium in the UK (end 1979) were some 20,000 tonnes, which if used in a commercial fast reactor programme would have an energy equivalent of 40 x 10^9 tonnes coal (equal to some 400 years' supply at current UK coal extraction rates or the whole of the estimated coal reserves of the UK) (58). In France the domestic dependence on imported fossil fuel jumped from 36% to 77% between 1955 and 1976; the Messmer plan of February 1975 called for the construction of 40 nuclear power plants to produce 45,000 MWe by 1985 and so provide some 55% of total electricity production and 25% of total energy needs. While this target was subsequently reduced to 20% as the power station programme fell behind schedule, by May 1981 France had 18,000 MWe installed and in operation, 30,000 MWe under construction and 15,000 MWe on order (59). The 55% target had been passed by the end of 1985 (see above). In addition, the 1,200 MWe Super Phénix fast reactor at Creys-Melville was planned for commission at the end of 1983. In fact, Super Phénix went critical in September 1985 and connection to the grid was scheduled for early 1986 (60). The nuclear programme would require by 1995-2000 some 1,000 tonnes of uranium per year which would then exceed existing French national and foreign resources, but would also have generated the accumulation of a 250,000 tonne stockpile of depleted uranium by 2000 (61). Parker (1978) also noted (paras. 8.34 and 8.35) that should nuclear power be used for a substantial part of electricity supplies "it is in the public interest that we should, unless the price of doing so is too great, minimise reliance on imported fuel", which implies, at least, leaving the reprocessing option open (62). The United States' position, in evidence to INFCE, was that reprocessing neither reduced dependence on foreign energy sources nor was a necessary prerequisite for final waste disposal. Its value lay only in providing fuel for fast reactors, and they were justified only where the electrical grid had attained a certain minimum capacity. Conversely, the German argument saw reprocessing as an indispensable component of safe waste disposal (63).

UK fast reactor research and development has been based on the 60 MWth (15 MWe) Dounreay Fast Reactor, between 1959 and 1977, superceded from 1975 by the 600 MWth (250 MWe) Prototype Fast Reactor also at Dounreay. The latter has a core fuel charge of some 4 tonnes, involving one tonne of plutonium plus 2 tonnes in the fuel cycle outside the reactor. Developing this to a commercial demonstration fast reactor would increase the core fuel charge to 20 tonnes, of which 6 tonnes would be plutonium (64). The fast reactor fuel fabrication plant at Sellafield has the capacity to take plutonium nitrate in solution (prepared on site at Dounreay) from which powder is derived to form granules to be made into fuel pellets. The alternative fabrication route loads fuel directly from granules formed by gel precipitation from plutonium-uranium nitrate solution; a pilot plant for this is under construction at Sellafield. The stock of plutonium available for civil use in the UK in early 1981 was approximately 12 tonnes (65), together with plutonium contained in irradiated fuel awaiting reprocessing; by then 6 tonnes had been used in the fast reactor research programme. The UK FBR research programme is now being reoriented to a joint European basis. In January 1984 an intergovernmental memorandum of understanding was signed (as the basis for further development of the fast reactor and the associated fuel cycle) by the UK, France, F.R. Germany, Italy and Belgium (66).

The major American research reactor was the Clinch River Breeder Reactor Plant using mixed oxide fuel, a project which began in 1969. The US breeder programme has an almost exclusive emphasis on plutonium cycle LMFBR, but experienced substantial setbacks following the Carter Administration's ban on reprocessing; the Clinch River project has since been cancelled.

France is the only Western nation to have developed fast reactor technology to a commercial scale with the Super Phénix plant now critical. To encourage the economic viability of this project, and so avoid being left with a purely scientific monopoly, France entered the Paris Agreement in 1977 with F.R. Germany (whose subsidiary partners were Belgium and the Netherlands). The Agreement was based on the exchange of technical information and the co-ordination of research and development, together with the creation of a joint marketing and licensing company SERENA (Société Européene pour la Promotion des Systèmes de Réacteurs Rapides à Sodium). The French participants are CEA and Novatome (a joint CEA-Creusot-Loire Subsidiary), the German company is Kenntnisverwertungs Gesellschaft Schnelle Brutreaktoren (KVG) composed of Interatom 51% (a KWR - Siemens Subsidiary), Gesellschaft für Kernforschung Karlsruhe 19% (GFK) plus Belgonucléaire 15% and Neratoom 15%.

The Phénix reactor - forerunner of Super Phénix - has reached a burn-up of up to 9.2% of the fuel, while the Dounreay PFR has achieved 7-8%. Fast reactor fuel will be more expensive per tonne than is the case for thermal reactors, but the costs per unit of electricity produced should be lower because of the high rating and long burn-up the designers expect to achieve. Similarly the capital costs of fast reactors will outweigh those of thermals but if uranium prices rise then the expected lifetime fuel input costs for a thermal reactor will be sufficient to justify the introduction of the fast reactor.

The LMFBR is not the only cycle which is possible: there are also gas-cooled fast reactors, and converter reactors operating on a Thorium/^{233}U cycle have also reached the research stage. ^{233}U is an alternative fissile isotope of uranium, not found naturally but produced from Thorium - ^{232}Th. Reserves of thorium are known to exist in large quantities in India, Norway, US, Canada, Brazil and Australia, with their total extent being perhaps as great as that of uranium (67). The research reactors originally operating on a thorium-uranium fuel cycle were high temperature gas reactors, helium cooled and graphite moderated. These converter reactors can utilise some 4% to 5% of the total energy available in thorium, and they operate with a high thermal efficiency. F.R. Germany has a prototype thorium high temperature gas reactor (THTR-300) which started generating electricity in November 1985 (68).

V.7 WASTE DISPOSAL

The final stage of the nuclear fuel cycle is the disposal of waste. In the UK the total level of nuclear waste holdings at the end of 1979 was given as:

Concentrated high level waste in liquid form	1,000 m^3
Fuel cladding sludges and miscellaneous waste from earlier processes	19,000 m^3
Plutonium contaminated waste	3,500 m^3
Wastes stored at power stations	20,000 m^3

(59).

Waste treatment in the UK is carried out at BNFL's Sellafield plant. In the USA at the end of 1975 some 1200 tonnes of spent fuel was being held at reactor sites and reprocessing facilities; there were plants at West Valley Hanford, Idaho Falls (the National Reactor Testing Station) and Richland (operated by the Batelle Memorial Institute). Waste treatment in France is carried out at the Atelier de Vitrification à Marcoule (AVM), whose process wastes have been developed in Germany by DWK at Karlsruhe.

If the fuel cycle is closed ^{238}U and plutonium are removed from spent fuel and stored for later use, leaving a comparatively small bulk of waste of high, medium and low level. The latter is essentially laboratory waste which may be buried in shallow trenches or encased in concrete within metal drums and taken out for dumping into the sea; this waste has been treated so that the activity associated with it is at a level low enough for discharge into the environment. The remaining medium and high level wastes are currently held as liquids in acid solution in water-cooled stainless steel tanks. (By 1980 ten tanks at Sellafield UK held some 770 cubic metres of high level waste which represented almost the entire accumulation from 25 years of nuclear research, development and power output).

The high level waste (associated with the fuel elements), has a relatively low volume but has both high heat output and, obviously, high radioactivity. Medium level waste (where the heat output is far less but the volume to be handled - including fuel rod cladding, waste from processing operations and laboratory equipment - is substantially greater), can be quite satisfactorily dealt with by enclosing it in a sufficient quantity of concrete, sealed in drums and then dropping in into the ocean.

The standard sequence of events in dealing with high level waste begins with storage of liquid form waste for a period of years in water cooled tanks, which allows the dissipation of some heat, and a decline in radioactivity. The most advanced technology for further stages has been developed in France at AVM, with the PIVER process of conversion of the liquid waste to glass cylinders. By April 1980 AVM had vitrified 230m^3 of fission products with a total activity of some 25m curies, and had produced 313 canisters comprising 108 tonnes of active glass (70). France is also planning second and third vitrification plants at Cap de la Hague for 1986 and 1987.

Atomic Energy of Canada Ltd. has continued research on vitrification, as has BNFL of the UK, who developed the HARVEST process. However, the first Sellafield vitrification plant will be based on the AVM process, because of the latter's successful commercial sized operation since 1978 (71).

In Australia research by A.E. Ringwood has concentrated on the possibilities of fixing waste in synthetic rock (SYNROC). There are now three bilateral research and development agreements concerned with Synroc, between Australia and Britain, Japan and Italy (72). Swedish research work on waste disposal was based on the law passed in April 1977 which prevented the commissioning of any new nuclear power station unless it could be shown that a completely safe way of disposing of all waste products had been found. This is comparable to the position taken in the UK in the Flowers Report (Flowers (1976)) which argued that there should be no commitment to a large programme of reactors "until it has been demonstrated beyond reasonable doubt that a method exists to ensure the safe containment of long-lived highly radioactive waste for the indefinite future". The Swedish power industry formed the Nuclear Fuel Safety project (Karn Bransle Sakerhet) in 1976, and research followed the route of containment of waste in cannisters (possibly synthetic corundum which, it is estimated, should resist the leaching effects of groundwater for some hundreds of thousands of years), to be buried deep in stable geological structures. A referendum in 1979 in Sweden committed power companies to stop new orders, and phase out existing reactors by 2010.

The significance of vitrification lies both in the heat tolerance of glass and its ability to withstand groundwater and in the reduction in volume that is made possible. In the UK the Magnox reactors generate about 1,000 tonnes of spent fuel a year which is reprocessed very soon after arrival at Sellafield (to avoid corrosion of the cladding). This annual quantity of fuel would produce some $60m^3$ of high level fission product waste liquor for storage; this in turn would produce a bulk of $15m^3$ per year if vitrified. Similarly the AGR when fully operational should generate about 300 tonnes of uranium per year as spent fuel to be reprocessed at THORP; this would amount to $30m^3$ of high level fission product waste which would reduce to $15m^3$ if vitrified (73). Similarly an estimate for a 20 GW nuclear programme in the UK is that once vitrified the total high level waste would amount to less than $500m^3$. It is these very small quantities which justify the development of highly sophisticated capital intensive waste management techniques.

Once converted to glass the cylinders are enclosed within steel cladding; these cylinders are then to be subject to further artificial cooling (either air or water) in stores which will allow inspection for a further period of possibly up to three decades. The length of time the waste is stored in each repository will determine how far it cools as will the quantity and type of waste (how much is fission product) formed into each glass block. After this cooling period the waste would be finally sealed and deposited in the ultimate permanent repository (possibly involving further titanium and lead shielding to guarantee even greater security).

These canisters will remain hot over centuries, but the temperature will gradually decline to the original level of the surround: "The overall level of radioactivity reduces to a very low figure within a few hundred years. Indeed in a few thousand years it reduces to the order of that in the original ore from which the fissile material in the fuel elements is fabricated" (74). It is the fission products which are responsible for the radioactivity and heat in the first few hundred years of life of the waste: but the total activity of these fission products (such as strontium 90, Cesium 137, iodine 129, krypton 85) has reduced by a factor of about ten million 700 years after production. What remains is the α-activity of the activides which, while a substantial cancer risk in very small quantities, is easily contained. The significance of this for the area to be devoted to waste disposal is shown in the comparison given in Institute for Energy Analysis (1979). There it is stated that at the time of solidification each cubic foot of waste is some 10^5 times more radioactive than a cubic foot of natural uranium; the decline in radioactivity will be such that after 1,000 years the activity in the waste will be 150 times that of the original uranium which produced the waste. This would possibly allow the use of space between or slightly above old canisters for burial of new wastes. No decision has been reached on just where the final disposal of the waste will take place, nor is there any pressing need yet for such a decision, as a period of fifty years is perfectly feasible between vitrification and final storage (75). One hundred years of cooling would have dissipated the bulk of the decay heat and increased by 30 times the number of canisters to be buried in any one area. Cohen (1977) discusses the area which would have to be devoted to waste disposal arguing that a 1 GW nuclear plant would create waste which would fill ten canisters each year of its operation. If each canister occupies 100 square metres then the year's waste will need 1000 square metres. He then estimates that an all nuclear US electric power system (of 400 1000 MW plants) would produce in total, waste canisters occupying less than half a square kilometre each year. But as argued above, delaying burial would allow the heat output of each canister to fall substantially so reducing the space required for heat dissipation. Three major possibilities are: on or under the ocean floor or burial on land. The ocean itself evidently represents an ideal means of heat transfer and dilution of activity, although with blocks designed to resist corrosion or decay for more than 500 years, the latter should not be of relevance. Burial beneath the ocean floor loses the benefit of heat removal but the sediment might be expected to absorb any leakage.

One area proposed for land burial is deep in deposits of hard rock. Once there the only routes for radioactivity to reach man would involve leaching into groundwater from a corroded or broken container, or a natural (or man-induced) catastrophe. While deep in the rock structure - chosen for its geological stability and predictability - the heat transfer would be slow which might imply extra stress on the containers, analysis in Sweden shows that failure of a single container would cause a change in the level of radiation within the local variations occurring naturally in the areas likely to be used. Catastrophic changes in rock structure are predictable by geologists within the time period when the waste containers would represent the greatest risk, and deep burial would minimize the possibility. The significant point here is that environmental conditions in rock formations 600 metres below the surface are not comparable with those on the surface; at that depth the "characteristic time intervals required for any substantial change are of the order of millions of years" (Cohen (1977)). Areas chosen because of their stability and freedom from groundwater are likely to remain in that state over a few hundred years - in geological terms a short reasonably predictable period. A further possibility for waste storage is within a salt deposit as has been shown in a disused salt mine at Asse in West Germany. Since 1967 drums of low level waste have been dumped into the chambers left by the mineworking, and medium level waste has been stored in batches of drums shielded with several tonnes of concrete (76). The advantages of salt as a burial medium are that it can conduct heat satisfactorily; its presence indicates the absence of any flowing groundwater, and it moves gradually over time to cover totally whatever has been left in it so that eventually the drums will be completely encapsulated in salt with no access at all. Cost estimates for waste disposal will vary with the nuclear fuel cycle under consideration. Meckoni Catlin and Bennett (1977) estimate that "70% of the total capital cost of waste management is attributable to the solidification plant for high level liquid waste and the cost of disposal in a geological formation". Gordon and Baughmann (1979) use a waste disposal price of $100 per kilogram of spent fuel ($ 1975) for their once through model of the cycle, and $300 per kilogram to cover reprocessing activities and subsequent waste disposal (which must be considered in the light of the value of uranium and plutonium recovered for re-use). Thus Parker (1978) in estimating the operating cost of THORP, quotes a reprocessing plus vitification cost of £260,000 per tonne, from which £60,000 is subtracted as credit for recovered uranium; (implying a net reprocessing plus vitrification cost of $384 per kilogramme in $ 1978). Kroch's estimate (1980) for waste disposal costs range from $61 per kilogram of spent fuel from a CANDU reactor to $85 per kilogram for a LMFBR, ($ 1974). Jones (1984) presents a full discussion of latest cost estimates - based, unfortunately, on assumptions of nuclear expansion that is both delayed and, now, unlikely. A NEA Report (77) (focusing primarily on the fuel cycle for PWRs) gives detailed cost estimates for all stages of the cycle. In particular, the report argues that back end services are both predictable comparatively minor in their contribution to total costs, so that reprocessing is viable economically.

V.8 INTERNATIONAL ASPECTS OF THE NUCLEAR FUEL CYCLE

International trade in all aspects of the nuclear fuel cycle has been common since the 1950s with transfers of research technology and materials from Canada, UK, USA, ("by mid 1976 14 supplier countries had over 100 agreements in force with other countries and some Third World countries were also beginning to give nuclear assistance to fellow developing countries") (78), although increasingly subject to debate because of the possibility of its becoming either the cause or the means for the proliferation of weapons. The International Nuclear Fuel Cycle Evaluation (1980) was set up in October 1977 as a technical study of how elements of the nuclear fuel cycle might be abused for purposes of weapons production. It is evidently not necessarily the case that a nuclear electricity programme is the forerunner of a nuclear weapons programme (Canada, FRG, Sweden). "The route to a nuclear weapon through the commercial fuel cycle has not been chosen by any of todays weapon states. Water reactors produce an inferior material for weapons" (79). Diversion of materials from an electricity programme would increase the complexity and risks of weapons design as the materials would not be suitable and it is not obvious that the development of nuclear weapons has been more possible anywhere because of a previously existing power programme:- "a state that had no nuclear power industry would not be expected to acquire nuclear power generation facilities for the sole purpose of obtaining weapons material, unless it wanted to conceal its intentions ... it is by no means clear that concealment would be easier than constructing special facilities ..."(80). However, the strategic and prestige effects of the possession of weapons capabilities means that risk of diversion exists and is increased by international trade in the nuclear fuel cycle.

In May 1981 it was announced that since 1971 the UK had exported 1,280 kg of plutonium produced in the UK to Belgium, France, FRG, Switzerland, Japan and the USA. In addition 1,930 kg of plutonium derived from irradiated fuel imported and reprocessed by BNFL under contract had been exported to the customer or a country nominated by the customer (Belgium, Canada, France, FRG, Italy, Japan, USA). This plutonium was for civil use in research and development in fast reactors or recycle in thermal reactors. The figures given were (81)

Plutonium Exports	3,210 kg	
Plutonium Imports	560 kg	
Highly enriched	(> 40% U235)	Uranium exports 660 kg
Highly enriched	(> 40% U235)	Uranium imports 640 kg

In the 1950s and 60s France exported a research reactor to Israel, a graphite/gas reactor of 497 MW to Spain, a PWR of 870 MW to Belgium and a reprocessing plant to Japan (Tokai Mura) to enter operation in 1977. In the mid 70s there were exports of PWRs to Iran and South Africa, of reprocessing plant to Pakistan and South Korea and of large research reactors to Iraq and Iran (82).

In 1974 India exploded a nuclear device built using fissile material from a Canadian supplied heavy water reactor (an efficient producer of plutonium) and heavy water supplied by the US (83).

A remarkably comprehensive nuclear contract was negotiated between F.R. Germany and Brazil in 1975, under which Brazil agreed to buy a complete nuclear fuel cycle, from prospecting through production of uranium compounds, enrichment, construction of power stations and reprocessing. The provision of enrichment and reprocessing facilities has caused concern as each could be diverted from civil use to production of weapons grade material (highly enriched uranium or separated plutonium), although Brazil has pledged that this will not be so.

A reaction to the dangers of uncontrolled nuclear fuel cycle trade was the formation of the "London Suppliers Club" in 1975/76 which began with meetings of representatives of industrial nations exporting facilities, materials and services related to the cycle. Initial participants were Canada, France, FRG, Japan, UK, USA, USSR and this membership gradually broadened to fifteen member nations (Belgium, Czechoslovakia, GDR, Italy, the Netherlands, Poland, Sweden and Switzerland). The London Club established a common code of conduct in the form of a set of guidelines requiring recipient nations to subject the use of "sensitive" imported materials to IAEA safeguards and to guarantee not to use these items in the manufacture of nuclear weapons.

The guidelines also required restraint in international trade in sensitive nuclear technology (particularly enrichment and reprocessing) but since they are part of an agreement and not of a treaty they have not prevented the export of such technology.

The second major element in control over the undesirable possibilities surrounding international fuel cycle trade is the 1968 Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which was an attempt to freeze the number of nuclear weapons states (then five: USA, USSR, UK, France, China, of which France and China have not signed the NPT). By May 1980 there were 113 parties but the force of the NPT in achieving its objectives lies in encouraging non-member nuclear weapons states (such as India, Pakistan, Israel, South Africa) to accept its articles and in expanding and improving the powers of the IAEA inspectorate in its detection of any diversion of fissile material from civil power programmes. The USA Nuclear Non Proliferation Act (1975) operates the safeguard of banning nuclear exports unless it can be shown that such exports can satisfy non proliferation commitments by not representing a possible weapons danger. Enrichment technology (and the export of significant amounts of highly enriched uranium) and reprocessing technology (and plutonium export) are embargoed under the Act. It has been argued that this restrictive export policy serves to amplify the inequalities between nuclear weapons states and non-nuclear weapons states. Where proliferation in the NPT meant the acquisition of nuclear weapons, under the Non-Proliferation Act it is redefined as the "capability of acquiring nuclear weapons" - a definition which would have rendered the negotiation of the NPT impossible had it been used there.

The Carter Administration also stopped domestic reprocessing of spent fuel prior to the investigations of INFCE. One justification for this ban lies in the resource estimates. Each 1 GWe LWR requires some 5500 tonnes of uranium in its expected 30 year life. The Carter Administration's argument was that with current resource estimates, gradual increases in reactor orders and a reactor construction time of some 10 years there would be adequate fuel to last well into the next century, without any need for reprocessing. Those studies which showed that recycling of uranium and plutonium in LWR was only marginally attractive at best and was probably not economic, reinforced this conclusion.

Thus one view of the nuclear fuel cycle is that proliferation risks would be greatly reduced if states had no access to further enrichment or any reprocessing plant. This view would support the adoption of the once-through fuel cycle leaving plutonium unseparated in spent fuel; such a position is adopted in SIPRI (1980) where it is claimed that "the fact is that reprocessing at present has little civilian utility, but could have serious military implications".

There seem to be two major alternative solutions to this NPT based constraint on reprocessing. The first, proposed by Marshall (1980 a and b), considers the possibility of using the fast reactor (which would obviously be prohibited by the non-existence of plutonium a ban on reprocessing would imply) as a proliferation and terrorist-proof incinerator. The spent fuel rods newly extracted from a reactor represent a radiation hazard so extreme that it is safe from any threat of theft. Yet once stored for some years as waste, the level of radioactivity declines, eventually to a point where handling would be possible for a period long enough for theft to take place (ignoring other safeguards). The fast reactor if constructed commercially would operate as a form of incinerator for plutonium in that the plutonium actually enters as a fuel to be consumed. The simultaneous creation of plutonium within the reactor is presumably not directly a terrorist risk since it has the same drawback mentioned above of being in fuel elements containing fission products so intensely radioactive that they would be unapproachable. If in the process of recycling, the plutonium bearing fuel rods were "spiked" with powerful gamma emitters, it would remain unapproachable, but would not be of any less value as a fuel. If combined with IAEA monitoring of movements of fissile material this would act to prevent diversion.

The second alternative is the internationalization of sensitive aspects of the nuclear fuel cycle (84). Thus Kaiser (1980) writes "today it is generally agreed that the multinational approach could improve the existing control system in several fields since multinational control of installations is in principle considered to be more proliferation proof than purely national control, particularly in the sensitive fields".

The IAEA study project on regional nuclear fuel cycle centres (RFCC) "envisage several countries joining together to plan, build, and operate facilities necessary to service the back end of the nuclear fuel cycle" (85). There would be other benefits to be gained from adoption of this approach: economies of scale in reprocessing mean that such a plant operates optimally on a throughput of about 1,000 tonnes a year of spent fuel, a quantity which would be available on an international basis. "The unit total cost of reprocessing and recycling operations using a 1,500 tonne/year reprocessing plant is about 40% lower than with a 500 tonne/year plant" (86). International regionalisation of reprocessing would simultaneously achieve the economies of scale and limit any incentive for the construction of small reprocessing plants so limiting the number of purely national facilities. Large economies of scale are also claimed for RFCC in waste management: cost reductions per tonne of fuel processed can be lower by a factor of 4 to 6 in large plant; any increases in transport costs would be negligible. Similarly Kaiser (1980) argues in favour of multinational fuel banks to increase the security of supply and points out that as reprocessing spreads and more countries have the capacity to produce or process plutonium, the creation of an international regime for the storage of plutonium will become increasingly important.

V.9 SUMMARY

Georgescu-Roegen has characterised the exploitation of natural resources in his phrase the "hour glass of the universe" - once energy resources (for example) are used an available resource slips from the top of the hour glass to become waste in the bottom. Uranium has no major use beyond production of power. If burnt in thermal reactors and once removed as spent fuel disposed of as waste in a once-through cycle, the world's uranium resources represent a briefly lasting stockpile of low entropy in the upper half of the hour glass. If reprocessed and recycled in fast reactors the available energy - suitable especially but not merely for the generation of electricity - is multiplied dramatically. Economic analysis may be used to optimise of exploration and exploitation rates for uranium, the introduction date for fast reactors on a commercial scale and the size of plant to operate the "super-hard" technology involved; it may also point to international regionalisation as a source of economies of scale and limitation on diversion of civil nuclear material.

NOTES TO CHAPTER V

(1) Greenhalgh (1980)

(2) Camp (1980)

(3) Lellouche (1980)

(4) ATOM 342 April 1985 p 14

(5) ATOM 347 September 1985 p 21

(6) ATOM 353 March 1986 p 17

(7) ibid p 17

(8) ATOM 352 February 1986 p 17

(9) ATOM 296 June 1981; Financial Times 23.9.81
Also see Greenhalgh (1980) and Energy Systems Program Group (1981) for a discussion of using nuclear reactors to provide process heat.

(10) ATOM 277 November 1979 p 294 and Financial Times 18.7.80

(11) Eden et al (1981)

(12) Nuclear Energy Policy Study Group (1981)

(13) ibid

(14) OECD 1978

(15) A discussion of this approach to analysis of uranium availability, together with a discussion of the possibilities of exploiting the vast reserves of very low grades of ores where "the problems of recovery are at least as forbidding as the quantity is attractive" is given in Energy Systems Program Group (1981)

(16) see Solow (1974a)

(17) ATOM 297 July 1981 p 185; and International Atomic Energy Agency (1980)

(18) Energy Systems Program Group (1981)

(19) Kaiser (1980)

(20) COGEMA was created 19.1.76; it is 100% owned by CEA and exists to operate all industrial and commercial activities concerned in the nuclear fuel cycle and so is separate from the public service duties of CEA

(21) Commissariat à l'Energie Atomique Annual Report 1978

(22) ATOM 277 November 1979 p 305

(23) see Lellouche (1980)

(24) see Hackel (1980)

(25) ATOM 345 July 1985 p 17

(26) see Treverton (1980)

(27) Energy Systems Program Group (1981)

(28) Gordon and Baughman (1979) p 240

(29) ATOM 277 November 1979

(30) Financial Times 19.6.1979

(31) see OECD 1978

(32) Financial Times 19.6.1979

(33) Financial Times 18.8.1981

(34) Gordon and Baughman (1979); also see Treverton (1980)

(35) Energy Systems Program Group (1981)

(36) see Greenwood et al (1980)

(37) The Energy Systems Program Group (1981) estimate for 1978/9 aerodynamic capacity was of the order of 6000 SWU per year in pilot or laboratory facilities. The possibility for South African expansion to 5 million SWU per year is stated in Nuclear Energy Policy Study Group (1981)

(38) Nuclear Energy Policy Study Group (1981)

(39) Financial Times 27.7.1979

(40) ATOM 287 September 1980

(41) British Nuclear Fuels Ltd. Annual Report 1980/81

(42) Nuclear Energy Policy Study Group (1981)

(43) Hansard 3 March 1980

(44) ibid

(45) Parker (1978)

(46) Cohen (1977)

(47) ATOM 277 November 1979 p 238

(48) see Lellouche (1980)

(49) see Hackel (1980)

(50) ATOM 269 March 1979 p 70

(51) in Nuclear Energy Policy Study Group (1981)

(52) see Lellouche (1980)

(53) Hansard 3 March 1980

(54) Nuclear Energy Policy Study Group (1981)

(55) ATOM 277 November 1979 p 298

(56) ATOM 297 July 1981 p 185

(57) Hansard 3 March 1980

(58) ATOM 281 March 1980 p 62

(59) ATOM 297 July 1981 p 184

(60) ATOM 349 November 1985 p 20

(61) ATOM 281 March 1980 p 62

(62) Parker (1978) paras 8.34 and 8.35

(63) see Kaiser (1980) and Nuclear Energy Policy Study Group (1981)

(64) ATOM 291 January 1981 p 14

(65) Hansard 6 April 1981

(66) ATOM 351 January 1986 p 55

(67) Treverton (1980) and Energy Systems Program Group (1981)

(68) ATOM 352 February 1986 p 17

(69) Hansard 23 April 1980

(70) ATOM 290 December 1980 p 310

(71) ATOM 298 August 1981 p 204

(72) ATOM 353 March 1986 p 19

(73) Hansard 3 March 1980

(74) Second Annual Report of the Radioactive Waste Management Advisory Group (1981)

(75) ibid

(76) Financial Times 24.11.1980

(77) quoted in ATOM 347 September 1985: NEA The Economics of the Nuclear Fuel Cycle 1985

(78) SIPRI (1980)

(79) Camp (1980)

(80) Greenwood et al (1980)

(81) Hansard 14 May 1981

(82) see Lellouche (1980)

(83) see SIPRI (1980) and Maddox (1980)

(84) see for example Institute for Energy Analysis (1979), Kaiser (1980), Meckoni et al (1977), Walker and Lonnroth (1983)

(85) Meckoni et al (1977)

(86) ibid

CHAPTER VI

POLICY IMPLICATIONS OF SOCIAL COST BENEFIT ANALYSIS

VI.1 INTRODUCTION

The central theme of this chapter is that major economic decisions require objective and full economic analysis, and in the case of nuclear power this implies a cost-benefit study whose coverage is discussed. The chapter is divided into 5 sections each dealing with an important underlying element of the framework of a cost-benefit analysis. Central problems are highlighted - particularly those concerning forecasting and the valuation of intangibles - and the difficulties they present for the analysis (and the resultant criticism of any such study) discussed. In some cases suggestions are made to improve the analytical process, elsewhere the consequences of essentially insoluble problems are noted. The conclusion is that the economist may (and should) use the route of clear, objective analysis of costs and benefits of a project as a major and important influence over the formulation of economic policy in any field of energy, and certainly in the case of nuclear power.

VI.2 ENERGY SUPPLY

VI.2.1 Energy and Economic Growth

The starting point of the social cost benefit analysis (SCBA) must be the decision on how to frame the question that it will be designed to answer. The analysis of whether or not the Electricity Supply

Industry (ESI) should have more nuclear power plants, constructed over one or two decades, clearly has implications which could be extended almost limitlessly. Accordingly the choice of which to include as significant and which to ignore as irrelevant will define the breadth, structure, and, in terms of policy, the value of the analysis. Independently of whether the UK is experiencing an energy 'shortage' or 'glut', or of whether one such situation is predicted for the future, the significance of current and future total energy supply (and the integration of its constituent parts) for economic growth and development is necessarily a fundamental part of the question asked of the SCBA. The USAEC (1974) study, for example, takes the view that what is at issue is "not whether a unit of electrical energy should be produced, but how it should be produced" (1), so that benefit is defined to be the quantity of electrical energy produced. This position is evidently debatable - and that is precisely what the SCBA can do, provided that its framework encompasses the area of energy supply. [In contrast, the Roskill Commission (1968) was set up to undertake a SCBA of a third London airport - but was not required to consider whether such an airport was actually needed - (2)]. In discussing the Sizewell B Inquiry Purdue et al (1984) argue that since a PWR, if built at Sizewell, would be intended by the CEGB to be the first of a series, then the Inquiry had inevitably to consider the question of future energy supply.

That the provision and role of energy should be made an explicit part of the SCBA is further highlighted by the regularity of statements in the literature arguing that economic growth and energy supply are strongly interrelated and that the former will certainly be compromised and quite feasibly prevented by constraints on the latter. An ethical viewpoint is taken by Abbate (1979), who argues that in a democratic society, if people demand more energy, then, essentially, it should be provided (3). Others simply argue that energy demands will grow and assume implicitly that this should be met; the major question then becomes that of the means used to produce the output to satisfy the demands. Thus Morowski (1983) writes of "an obvious need to satisfy a growing or future need for electricity with less costly nuclear fuels or indigenous resources". Schurr (1984) in a brief review of how vital energy growth has been in world history as a means of removing constraints on economic growth and development, and so permitting technological change and innovation, warns of the possible irony "[could] energy supply - the constraint-breaker par excellence in the past - become a constraint itself?" (4).

Similarly the 'Flowers Report' (Flowers (1976)) considers: "Energy is a necessity for economic growth and higher living standards and there is a steadily rising world demand". (5) Starr (1982) writes "increased use of nuclear power is essential to provide a substantial portion of the electricity necessary for world economic growth" (6). Finally ATOM 309 (1982) quotes an OECD report: "Sustained economic growth is critically dependent on the availability of adequate energy supplies" (7). Once the energy and/or electricity supply is thus related to the standard of living, GDP and so on, an ability to expand the supply becomes self evidently desirable. Moreover Maxey (1979) (in one sense echoing Abbate (1979) in the same volume) points to the necessity of promoting economic growth as the poor "have a right to basic material well-being for which energy is the necessary condition"; "Conservation ... [is] an option for and a recommendation made by the "haves" in our society ... it is a laudable programme for the affluent and for the middle class" (8).

VI.2.2 The Energy Coefficient

The argument relating the growth rates of economic activity (GDP) and energy consumption has become particularly contentious since the effects of the first OPEC-induced oil-price shock of 1973/4. The relationship, known as the energy coefficient is the ratio of the percentage increase of energy use per annum, to the percentage increase in real GDP (corrected for temperature and expressed per capita); as such it corresponds to the output elasticity of energy demand. A scatter diagram of this elasticity for the UK 1950-1973, published in the Digest of UK Energy Statistics (9) shows the annual observations to grow fairly smoothly, and to fit very well a line giving a constant (theoretical) energy coefficient of 0.65. The closeness of the fit lends weight to the use of the energy coefficient for extrapolation and forecasting. However the relationship disappears after 1974; for example 1974-75 and 1979-80 the growth rates in energy consumption and GDP are both negative and all the post 1973 observations lie below the trend line which previously fitted the data well.

Allen (1976) and Hull (1981) argue that this is not an unexpected result. Allen calls the energy coefficient a "very crude elasticity" and Hull notes that for it to be a "sufficient and accurate description" of the determination of primary energy demands the only determinant of that demand would be GDP. This is just the ceteris paribus argument for any demand relationship: a change in income shifts the demand curve for a product and the previous price/quantity co-ordinate no longer obtains. Similarly changes in the real price of energy, the composition of GDP and the primary fuel mix have caused a (dramatic) shift in this relationship and the previous fairly straightforward trend extrapolations predicting isomorphic growth patterns in energy demand and economic activity also cease to hold true. The decline in UK manufacturing generally, and particularly in the highly energy-intensive iron and steel industries; the relative shift toward comparatively "low energy" service industries; real energy prices moving up rather than down; GDP growth beginning again only in the early 1980s, are all clear reasons for the instability of the energy coefficient and, hence, its rejection as a means of forecasting (10).

In the short term there is little doubt that this conclusion must be correct. The post-1973 energy coefficient for the UK became volatile and entirely unpredictable and no weight could be placed on it. However, Schurr (1984) and Meinel and Meinel (1979) both use much longer term data (for the United States in both cases), to continue to give strong backing to the energy growth/GDP growth correspondence. Both papers refer to the situation in the USA in the 1920s when the relationship showed a decline, and explain it by the introduction of new energy sources, new technology and a substantial shift upward in energy efficiency (11). The remaining data until 1973/4 confirm the relationship and the subsequent shift prompts Meinel and Meinel to argue that "...perhaps it is not possible to increase GNP while decreasing energy consumption" (12). Brookes (1972) successfully tested a hypothesis that the per capita useful energy coefficient tends asymptotically to unity with increasing economic sophistication, with "useful energy" defined to allow for changes in fuel mixes and the secular trend in energy efficiency. Clearly in the longer-term the trend growth of GDP is sufficient to provide sensible results and an approximately constant energy coefficient emerges. It may well be dangerous to draw short term conclusions but it is unlikely that anyone would try to do so in the 'shocked' conditions of the mid-1970s onward; and, moreover, a SCBA of a nuclear power programme is very definitely not concerned with the short term.

The post-1973 failure of the energy coefficient to serve as a useful relationship is also discussed in the Department of Energy (1977) where it is argued that the earlier, very close relationship (described above) is simply explained by increasing economic activity being a more significant influence on primary energy consumption that all other causal factors combined. Once prices rose, the demand relationships became more complex to deal with; demands, for example, were thought to be initially fairly elastic, but likely soon to become quite inelastic (as some cut back is cheap and easy; more becomes expensive and uncomfortable). Consumers are seen to adjust to price increases in two, simultaneous, ways: they both increase the efficiency of use of a fuel and reduce the amount of useful heat they are demanding. Hence, analysis of price elasticities and use of them for forecasting becomes particularly difficult. This problem is exacerbated by price effects being outweighed by supply constraints; the Department of Energy quotes nuclear power as a technology which will not be developed to its optimal (in a SCBA sense) level because of "managerial, environmental and political constraints" (13).

A different interpretation of the energy coefficient is given by Sweet (1983a), where it is argued that any relationship developed in the period 1950-1974 is the outcome of unique features of that time. These included rapid industrial growth (and an increase in the nation's capital stock); road transport developments and consumer durable expansion; and a falling real price of energy. But, Sweet argues, now industrial production is in decline (and especially so in the traditional, energy intensive sectors such as iron and steel and aluminium), while the transport and consumer durable sectors have reached saturation. Rising real prices of all fuels have created much more price sensitivity than had previously been the case and have stimulated the development of energy economy and a demand for energy efficiency (14).

VI.2.3 The Market Share of Electricity

Odell (1980) also accepts that since 1973/74 the energy coefficient has collapsed but an equivalent relationship between the consumption of electricity and economic activity has, if anything, strengthened. This point is also emphasised by Weinberg (1984) in showing the decline in the energy/GNP ratio worldwide with a simultaneous increase in the electricity/GNP ratio (15). This result he explains by the fall in the relative price of electricity and the switch to using electricity in many process industries (where it has been found to perform better and improve productivity). These are precisely the arguments advanced by Day (1980). In a paper concerned with forecasting future electricity consumption Day notes the "favourable trend expected in the relative price of electricity and fossil fuels", and "developments in electrotechnology which ... seem likely to promote a major increase in the use of electricity for industrial process heat" (16).

The declining real relative price of electricity and the increasing penetration of electricity in the overall energy market can be seen to be the case by reference to figures VI.1 to VI.6. Figure VI.1 shows nominal prices of fuels, and even here the dramatic increase in the price per therm for electricity can be seen to have peaked; the more useful real price data are shown in figure VI.2 where it becomes clear that in fact electricity prices in real terms are generally following a long run downward trend - a trend mirrored by gas until 1974. Since that date gas, oil and coal all show more or less continuous up-ward

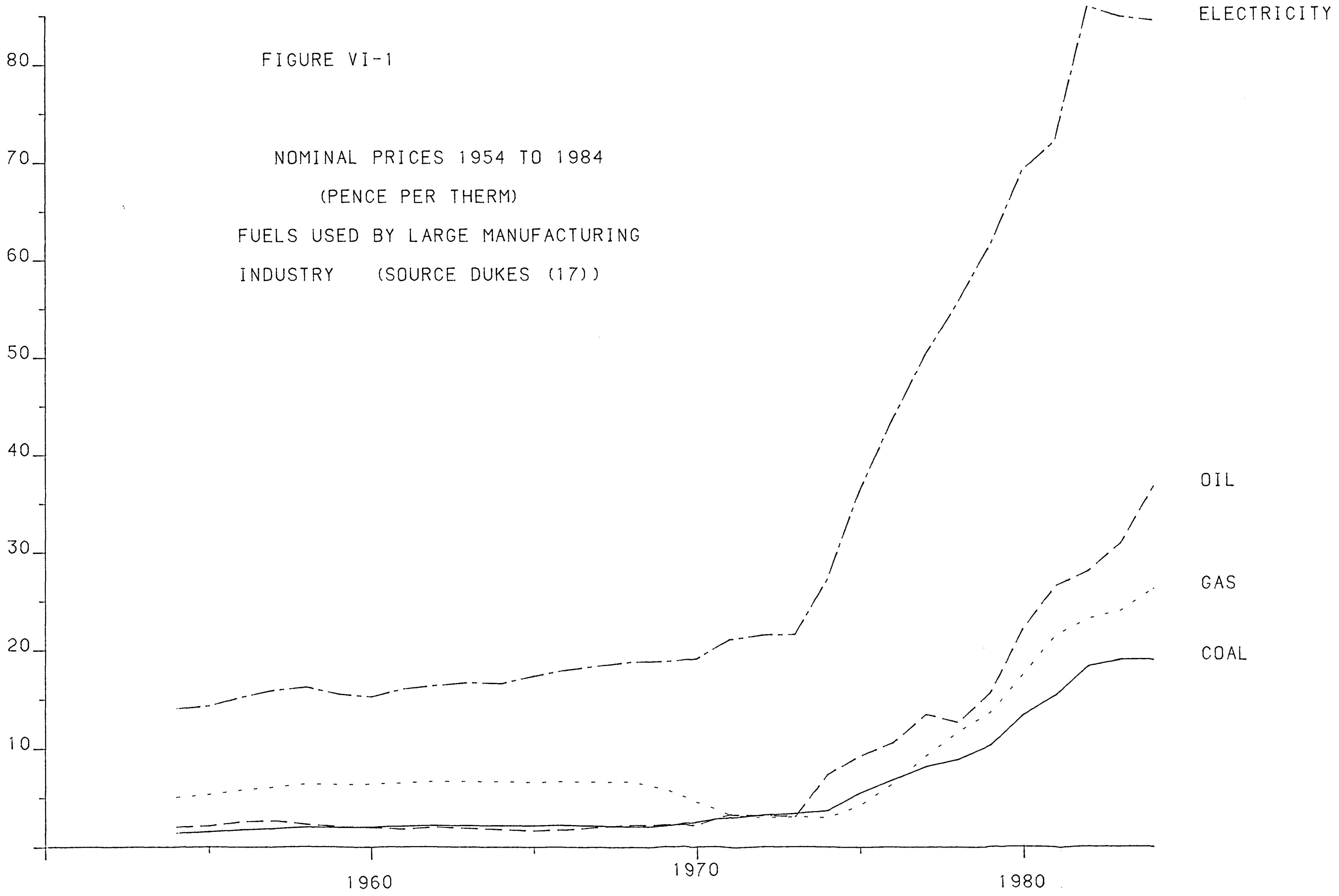


FIGURE VI-1

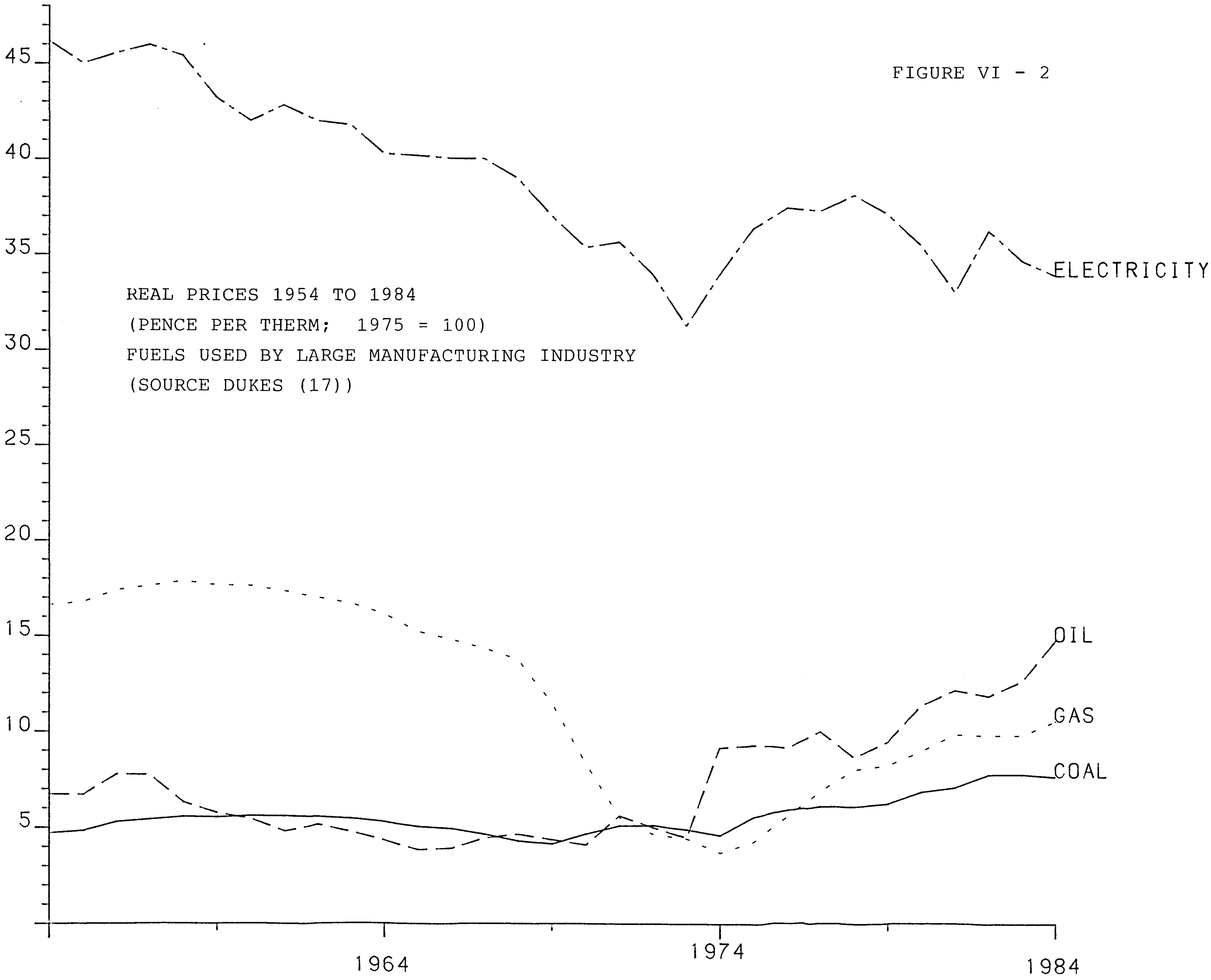
NOMINAL PRICES 1954 TO 1984

(PENCE PER THERM)

FUELS USED BY LARGE MANUFACTURING

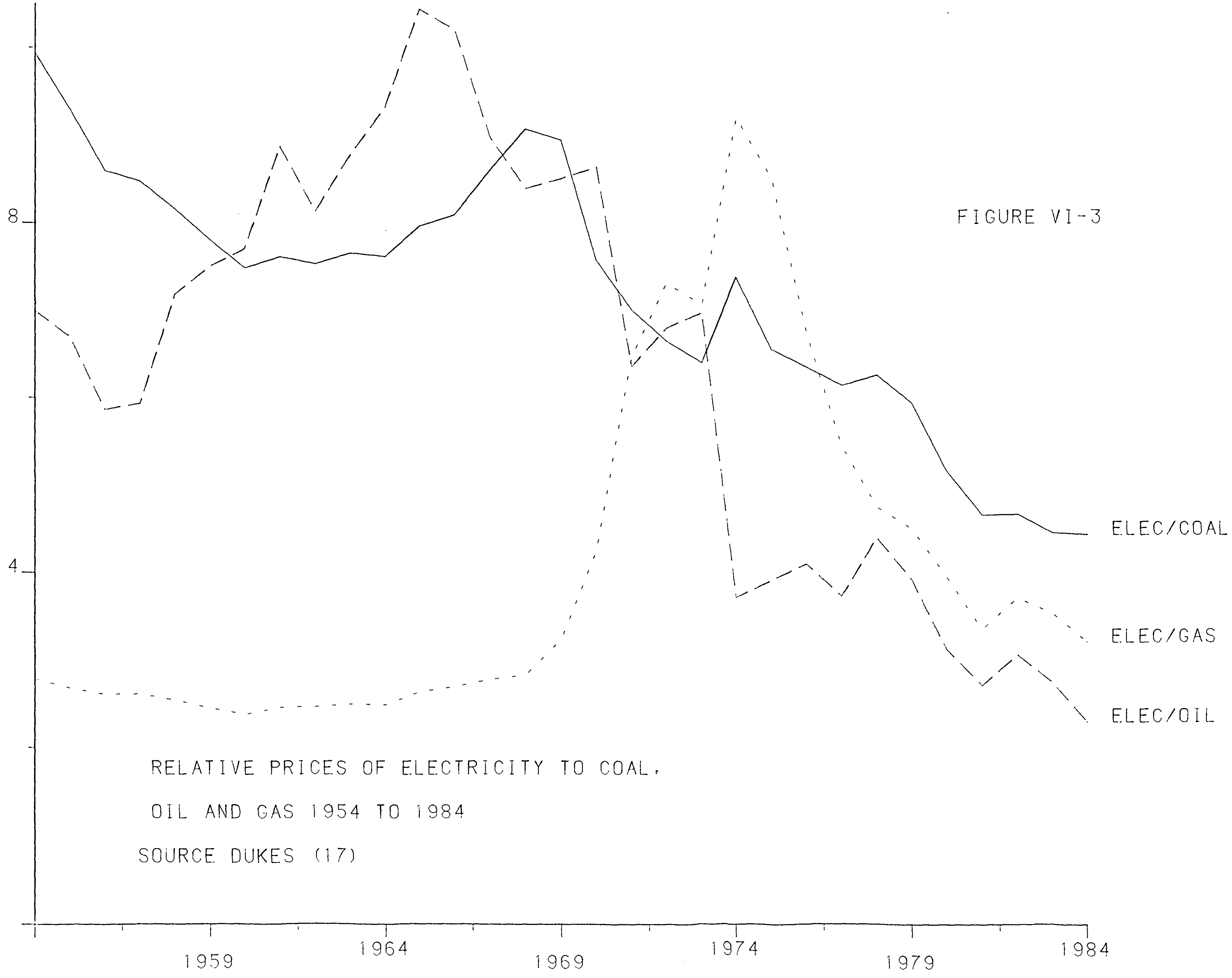
INDUSTRY (SOURCE DUKES (17))

FIGURE VI - 2



REAL PRICES 1954 TO 1984
(PENCE PER THERM; 1975 = 100)
FUELS USED BY LARGE MANUFACTURING INDUSTRY
(SOURCE DUKES (17))

FIGURE VI-3



RELATIVE PRICES OF ELECTRICITY TO COAL, OIL AND GAS 1954 TO 1984

SOURCE DUKES (17)

movements. In figure VI.3 the relative price of electricity to coal, oil and gas is shown for the period 1954 to 1970 when there is a dramatic rise from a ratio of 3.23 to 9.2 in 1974; the following decline to 3.21 in 1984 is equally rapid. The declining ratios of electricity/coal and electricity/oil begin in 1970 and 1967, respectively, and the final picture to emerge is one of increasing competitiveness for electricity and a corresponding growing probability of increasing market penetration and market share, as argued by Day (1980) and in the Electricity Council (1985) Medium Term Development Plan (18).

Further confirmation of this is given in figures VI.4,5 and 6 which show the market share of electricity in total primary energy consumption with and without the iron and steel industry (figure VI.4) and the relative growth rates of electricity demand and total primary energy demand (figure VI.6). The market share of electricity in total primary energy consumption has risen smoothly from 8.5% to 14.3% over the twenty two years; the percentages are, naturally slightly greater for the share in total primary energy excluding the iron and steel sector (from 9.9% to 15.1%). Figure VI.5 shows electricity consumption against total (non iron and steel) primary energy consumption in billions of therms per year. The same steady rise for electricity is again evident, although the total consumption is showing a fall from 1980 (from 56.7 billion therms in 1979 to 53.72 billion in 1980 to 51.15 billion in 1984).

Figure VI.6 shows the growth rates of total energy and electricity consumption. Clearly they follow a very similar pattern, except that from 1982 electricity has shown a positive growth rate (1.6% in 1983, 2.9% in 1984) while total energy has continued with a negative growth

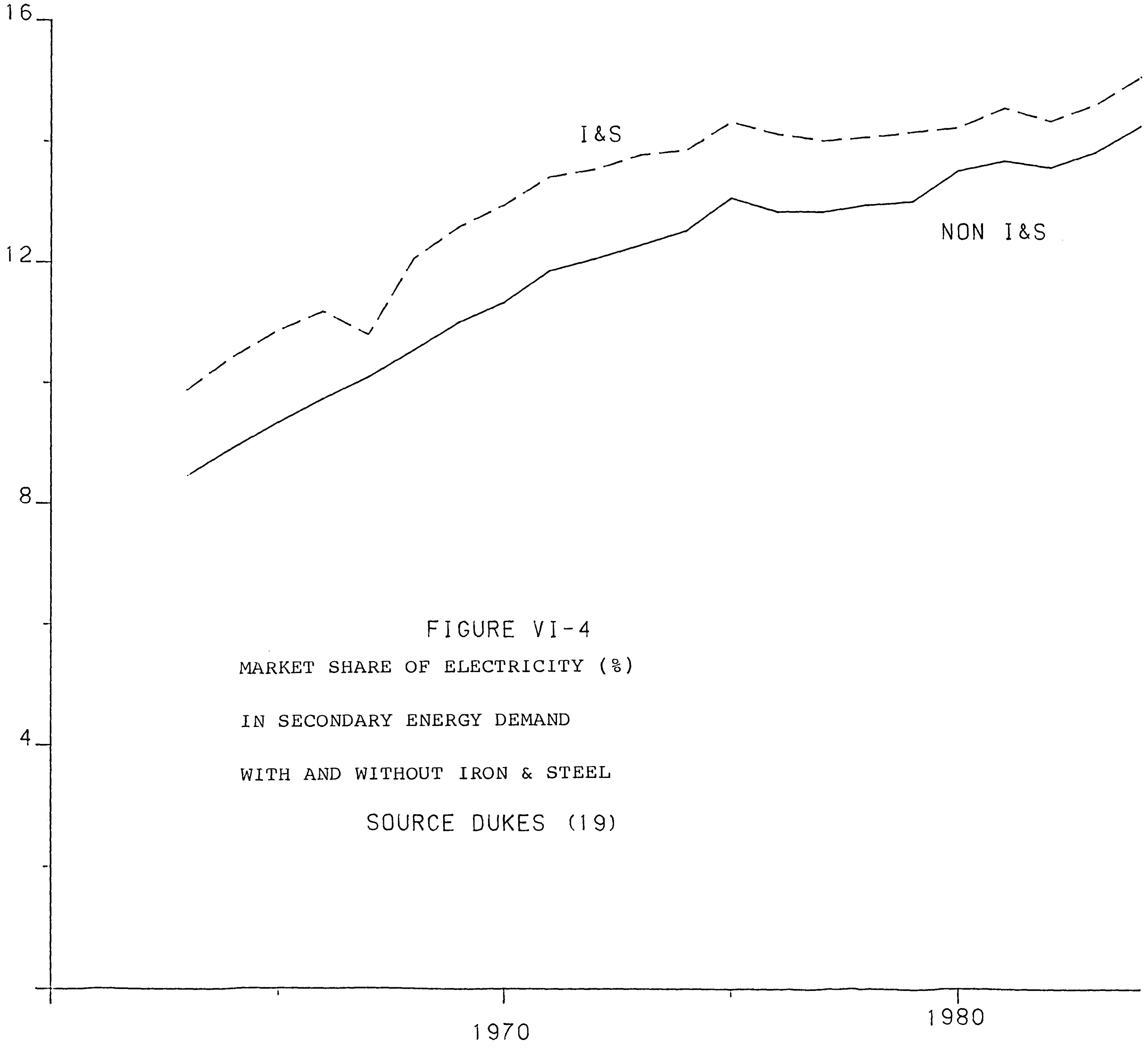


FIGURE VI-4

MARKET SHARE OF ELECTRICITY (%)

IN SECONDARY ENERGY DEMAND

WITH AND WITHOUT IRON & STEEL

SOURCE DUKES (19)

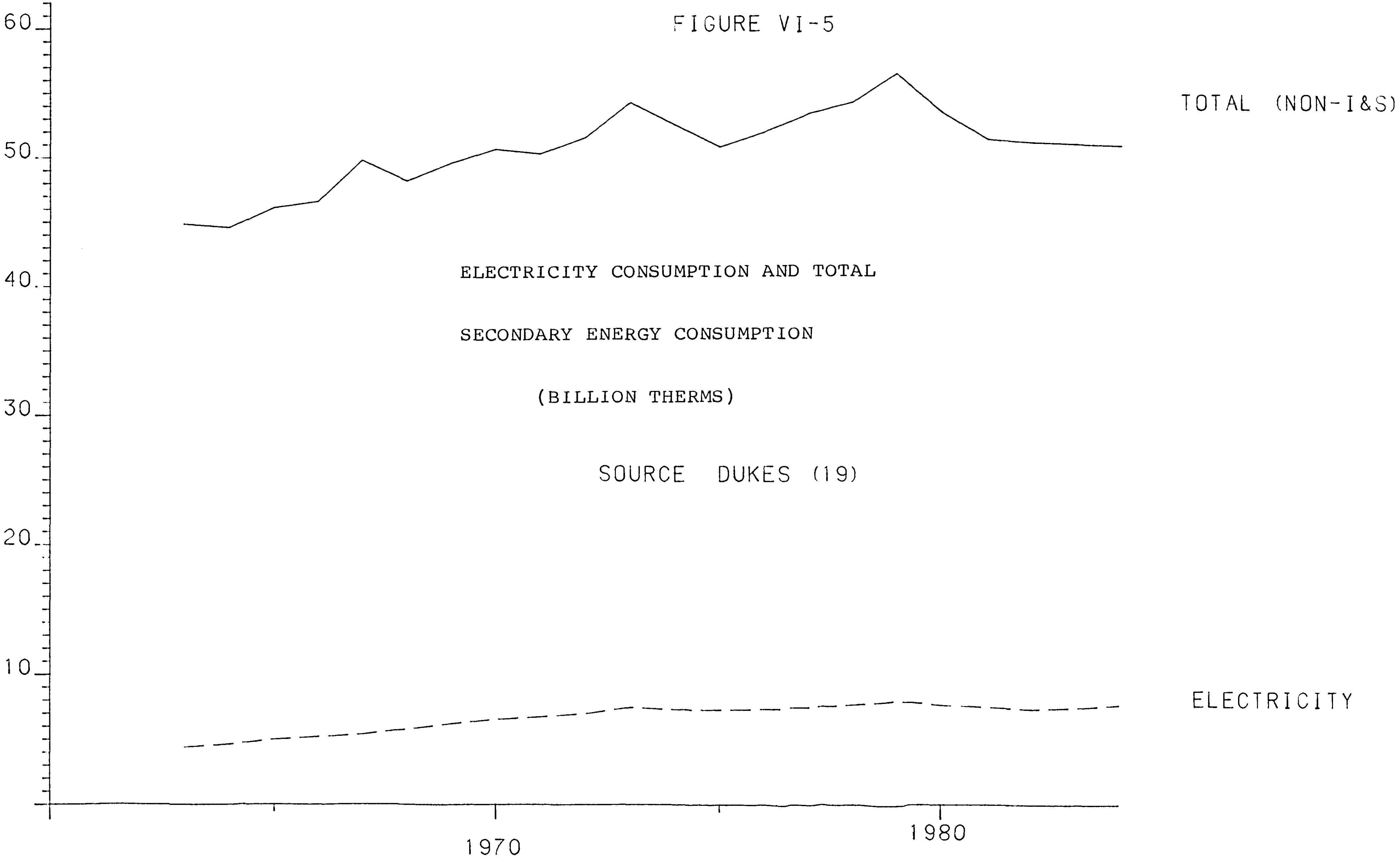


FIGURE VI-5

ELECTRICITY CONSUMPTION AND TOTAL
SECONDARY ENERGY CONSUMPTION
(BILLION THERMS)

SOURCE DUKES (19)

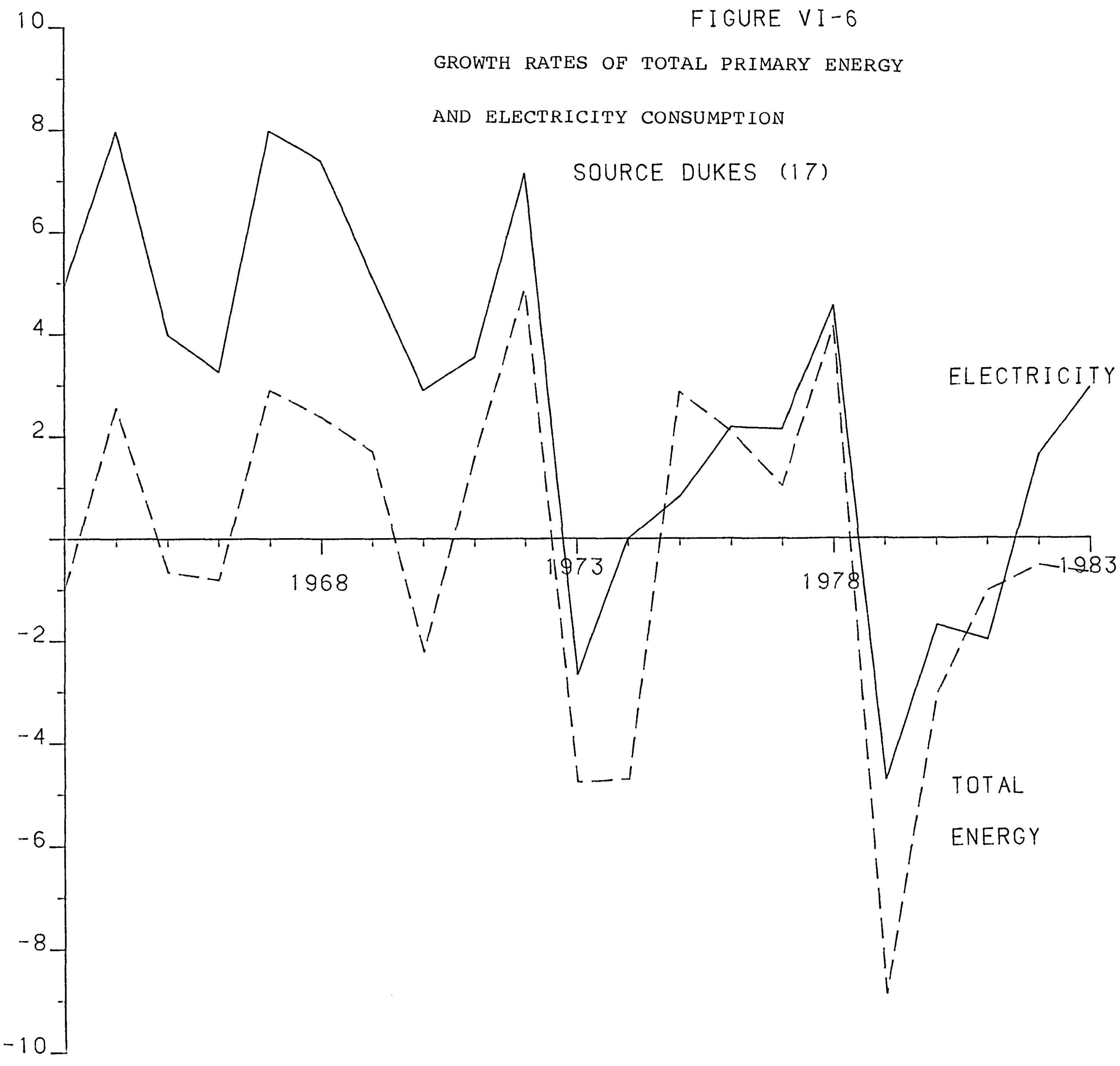


FIGURE VI-6

GROWTH RATES OF TOTAL PRIMARY ENERGY

AND ELECTRICITY CONSUMPTION

SOURCE DUKES (17)

rate history since 1979/80. In general the growth pattern of electricity over the period is to grow rather faster than total energy in peak periods, but not to experience the same slump in consumption when total energy growth rates turn negative.

However, in contrast to the optimistic analysis of Day (1980) it is also possible to predict a relatively limited growth future for electricity. [The specific topic of forecasting and its significance for SCBA is considered in a later section of this chapter]. Lonnroth and Walker (1979) point to the stagnant electricity market in most developed countries following 1974 and argue that the consensus view is that, while electricity demand will grow relatively more rapidly than will total energy demand (and hence relatively faster than other primary energy inputs), it will, nevertheless, be growing below trend. In addition to Sweet's (1983a) point on saturation of markets they note limited population growth and, contradicting Day (1980), they claim "There appear to be relatively few technologies and markets around to provide the stimulus for economic expansion" (20). They do point to the possible market expansion in domestic space heating - but that is an area which arguably changes the nature of electricity as a fuel, and as such is not a market where electricity penetration should be encouraged. This argument is based on the high energy quality of electricity being "wasted" in such a use. However since this market is based on 'off-peak' supplies the strength of the argument is very limited (21). A more profitable way of investigating this point might be to consider Berrie's (1983) view that a decline in the rate of change of demand is indicative of saturation (22). Appendix VI.1 shows maximum potential demand since 1960/61, but despite the decline in the early 1980s it is doubtful whether such a strong conclusion should be reached given the GDP experience over the period. Day's (1980) disaggregated analysis shows feasible demands in many industrial processes and might thus be treated as more reliable.

Thus, Starr (1982) notes a "continual shift into electricity as an energy form in commerce and industry" (23) and predicts a continuation of the electricity and economic growth rates relationship.

VI.2.4 Energy Supply, Economic Growth and Market Penetration by Electricity

In summary, this section argues that, despite volatility and unpredictability since 1973/4, there is a long term relationship between energy supply and economic activity which makes the question of energy supply directly relevant to any SCBA dealing with nuclear power. What is at issue may be described in terms of an "energy gap". Clearly a "gap" has no absolute meaning for an advanced economy as supply will always equal demand at some price. Instead it shows up in increasing energy prices acting to depress growth - it is not that the lights cannot be turned on, but that the future economic growth will be constrained. Brookes (1984) points to the potential damage which may be done to economic activity by a reduced availability of energy supply. The typical route by which such effects are transmitted is traced in the case of electricity by Starr (1982): electricity shortages are not apparent since generating plant is always available. The problem is, rather, that growing demand can be met only with increasingly expensive low merit-order plant which raises electricity prices; over time this will discourage electricity intensive industries from setting up or continuing to develop in the UK, and, generally, standards of living will be below what might have been the case - yet no absolute energy shortage will ever have appeared.

The second conclusion of this section is that the data do support the contention that electricity is gaining a bigger share of the primary energy market, and its price relative to oil and gas is declining. Additionally engineering-type forecasts of possible future areas for market penetration indicate opportunities for adding to the share. This is further evidence for framing the SCBA to analyse energy supply overall and the constituent elements of that supply when considering an expansion of nuclear power. Finally, the measure of benefit has been stated to be the electricity produced (partly as the ESI has a statutory duty to meet consumer demand). The argument that perhaps more and more electricity is not really beneficial must also be considered - that is, that electricity is "interfering in markets where it doesn't belong" - space heating, transport and so on. Flowers (1976) notes that a high electricity future (based on Department of Energy projections using an optimistic growth rate for GDP), would be wasteful in generating a huge amount of rejected low temperature heat at power stations (24). Given thermal efficiencies of 33% to 35%, dramatic increases of electricity supply also apply a big leverage to the increases of primary fuel usage. However, this is not the point at issue; what is being discussed is consumer demand based on income, relative prices and taste. In that case taking output as benefit is justified.

VI.3 FORECASTING

VI.3.1 Introduction

There are two, broad areas of forecasting relevant to the consideration of how to undertake a SCBA for nuclear power. These are forecasting future energy demands (both for total primary energy and the disaggregated demands for individual fuels), and forecasting the costs of providing the means to meet those demands. For the ESI those forecasts are not only crucial (since the industry requires secure supply to meet all demands at minimum (capital plus fuel plus operating) cost, to remain competitive itself and to provide its industrial consumers with the power they need at a cost which will keep their competitive edge), but also particularly difficult. The long lead times alone require the demand forecast to be accurate for at least six years ahead; furthermore the power stations may be expected to have a working life of thirty years, so their changing role in the merit order will also determine the revenue they may be expected to generate, implying forecasts undertaken for that lifetime. Thus, the ESI does not have the option of searching for investments with rapid payback, as the gestation periods of its power stations are inevitably long; and it is also required to produce estimates for a range of interacting variables into the comparatively distant future. It is not difficult to find statements in the literature which imply that the ESI is faced with an impossible task: "Forecasts over this period of time [30-40 years] cannot be made with sufficient confidence to justify the investment, and decisions which are based on such forecasts are, therefore, very open to error" (25); "clearly it is impossible to forecast the future with any degree of confidence" (26); "as forecasting extends quite far into the future it is impossible to quantify or formalise the evolution of all the determinants" (27).

However, it is also possible to find many demands that the ESI should nevertheless be undertaking the role of forecaster, from the least coercive: "those concerned with energy planning in government have to form a view on how the energy situation is likely to develop and make appropriate plans" (28); to a criticism from the IEA that the UK's failure to draw up long range forecasts puts the country out of step in international co-operation and removes a valuable guide for planning (29). Berrie (1984) actually presents both viewpoints; he cites a World Bank study on load forecasting, which shows up significant errors and a consistent failure of the forecasters to learn from those errors and then argues that plant extension programmes require load forecasts for every five years of the plant life with spot forecasts for even later years being useful.

VI.3.2 Economic Forecasting and CEGB Experience

The economic approach to forecasting lies in econometrics and the model and results of chapters II and III (above) can clearly be adapted to undertake simulation and prediction of price elasticities and substitution possibilities. The results to date provide information on system characteristics and contribute to the decision on future system fuel and input mix. Assumptions on these plus assumptions on future price trends and demand levels will allow estimation for future dates. There will thus be a series of interacting econometric forecasts - of load, of station mix, the structure of the merit order, the structure of expenditure on inputs, and so on.

The econometric approach is essentially extrapolation from a set of past data and is likely to be most accurate when the chosen variables are changing gradually and smoothly. In such a case the extrapolation of satisfactorily estimated relationships is likely to track actual events adequately over a fairly long period. Energy demand pre-1973 may be thought to have fallen into such a category, particularly given the relative stability of the energy coefficient (noted above). However, UK demand estimates proved then to be poor, and those of the ESI to be notoriously so. Table VI.1 shows CEGB forecasts of maximum demand and the outcome, in TWh. The gap is beginning to close but it is evident that the forecasts have always been substantially in excess of the outcome. This is indicative of a persistent optimistic bias in the forecasts which has been influenced neither by experience of error in the past, nor by exogenous shocks such as in 1973/74. The latter clearly represents a structural break and would be an obvious reason for the failure of econometric forecasts to fit. Indeed, the forecasts 1975/76 and 1976/77 are both shown to be over 30% in error in Table VI.1.

Table VI.1

Year Forecast Was Made	Year Being Forecast	Forecast Output TWh	Actual Output TWh	% Error
1965/6	1970/1	238.0	186.2	27.8
1966/7	1971/2	246.7	190.5	29.5
1967/8	1972/3	238.0	204.5	16.4
1968/9	1973/4	240.0	201.8	18.9
1969/70	1974/5	252.0	210.9	19.5
1970/1	1975/6	268.0	204.6	31
1971/2	1976/7	272.0	208.6	35.2
1975/6	*1982/3	265.0	206.7	28.2
1976/7	*1983/4	263.0	212.7	23.7
1977/8	1982/3	248.5	206.7	20.2
1978/9	1983/4	244.0	212.7	14.7
1979/80	1984/5	239.9	213.7	12.3
1980/1	1985/6	232.0		
1981/2	1986/7	220.5		
1982/3	1987/8	227.0		
1983/4	1988/9	229.5		
1984/5	1989/90	234.5		

CEGB Actual and Forecast Demand TWh

Source: CEGB Annual Report and Accounts 1965/6 to 1984/5

* Six year forecast

However, the particular problem with these demand estimates is that they are persistently wrong in the pre-1973 years when the econometric exercise might have been expected to be fairly successful; and (despite recent improvement) remain exceptionally high in years when the impacts of the oil price shocks and market instability should have been accommodated in the forecasting equations.

Table VI.2 shows the forecasts published by the CEGB for plant to meet forecast restricted ACS maximum demand. Again the immense optimistic bias in the forecasts is clear, as is the very long time required by the industry to introduce downward revisions. It is noticeable that it is not until the 1980s that a significant element of stability is incorporated in the estimate, and that the 1983/4 forecasts if contrasted with those made twenty years earlier in 1963/4, show a quite dramatically different future from that being forecast in the latter period.

Table VI.2

Year Being Forecast	Year Forecast Was Made											
	1961/2	1962/3	1963/4	1964/5	1965/6	1966/7	1967/8	1968/9	1969/70	1970/1	1971/2	1972/3
1962/3	31,373											
1963/4	33,695	33,533	33,118									
1964/5	36,593	37,292	36,294									
1965/6	39,561	40,479	39,847									
1966/7	42,932	44,517	44,150									
1967/8		49,101	50,788									
1968/9			56,173									
1969/70			61,000	59,000								
1970/1			66,800	57,500	54,000							
1971/2					58,500	55,000	54,000					
1972/3						59,200	54,000					
1973/4								54,000				
1974/5									53,200			
1975/6										54,000		
1976/7											54,000	
1977/8												55,000
1978/9												56,500

Continued Overleaf

CEGB: Exepcted System Generating Plant to Meet Forecast Restricted ACS System Maximum Demand (MW)

Continued

Year Being Forecast	Year Forecast Was Made											
	1973/4	1974/5	1975/6	1976/7	1977/8	1978/9	1979/80	1980/1	1981/2	1982/3	1983/4	1984/5
1978/9	56,500				44,500							
1979/80	57,500				45,600	46,200						
1980/1					46,900	47,000	45,700					
1981/2	61,700	54,000			48,200	48,000	45,800	44,000				
1982/3		56,000	52,000		49,500	49,000	46,200	44,800	42,900			
1983/4			54,000	51,500	50,700	50,100	46,800	45,400	43,000	43,200		
1984/5				53,000	52,000	51,200	47,300	46,500	43,400	43,700	43,700	
1985/6					55,200	52,400	47,900	47,300	43,800	44,000	44,000	44,500
1986/7						53,600	48,500	48,100	44,200	44,400	44,400	44,800
1987/8								49,000	44,600	44,700	44,700	45,100
1988/9								50,000	45,000	45,000	45,000	45,400
1989/90										45,400	45,400	45,700
1990/1											45,800	46,000
1991/2											46,100	46,400

CEGB: Expected System Generating Plant to Meet Forecast Restricted ACS System Maximum Demand (MW)

Source: CEGB Annual Report and Accounts each issue from 1961/2 to 1984/5

Appendix VI.1 presents similar forecast and out turn data for the CEGB, with the general conclusions as above.

The problem is not so much that the forecasts are wrong - it would be a simple exercise to take major economic forecasters' predictions and show them to begin to go awry when dealing with only comparatively brief intervals into the future. The Financial Times does this regularly with the Treasury forecasts compared to those of the London Business School, the Liverpool Model, the National Institute Model and so on. Rather, there are two particular difficulties specific to the ESI. The first is the inertia in the estimates: it takes so many years for a persistent optimistic bias to begin to be removed. This could be partially explained by the inertia of the industry itself - once investment decisions are made and put into action many years will elapse before a change of direction can be effected (a point which will be elaborated later). The second is that these five and six year estimates are seen to be wrong; yet the industry is also required to make fuel price estimates at least twenty years ahead; if a reactor is given an expected life of twenty five years and a construction time of seven years then the forecasting horizon becomes some thirty years. But since the forecasts highlighted in Tables VI.1 and VI.2 above are shown to be markedly wrong within five years, it is not surprising that forecasting "15 to 20 years ahead (is) a task which with hindsight can be seen to have been impossible" (30).

The experience of the forecasts may be investigated through the Annual Report and Accounts of first the Central Electricity Authority, then the CEGB (31). In 1956-57 the CEA were planning for an increase in generating capacity of 44% during the six years 1957-62, and for 6GW of nuclear plant to be in operation by the end of 1965; (by that date a total of 2.8GW of nuclear plant was operating). In 1962-3 (a year in which maximum potential demand was not being met, contrary to the case in 1956/7), the CEGB submitted to the Electricity Council (EC), estimates for future maximum demand based on a ten year trend of a 7.5% increase per annum, and an 8.6% increase of future energy requirements. But the EC was working on higher figures and the CEGB revised its estimates to 7.9% and 8.6% respectively, partly to take account of the NEDC objective of a national growth rate of 4% per annum, (a target backed by the government). The 1964 estimate for new generating plant was to bring 23.4GW of new plant into service by 1968. This was justified on two grounds: first to accommodate the results of achievement of the NEDC growth target and second as an "act of faith". It was acknowledged that the CEGB was acting before other sectors but in doing so would contribute to the growth that the capacity was designed to meet; (and ESI investment orders stimulated growth in the more depressed regions in the north of the country). The level of capacity predicted for 1968 was achieved in 1973/4 (and that predicted, provisionally, for 1970, at 66.8GW is 14% above the maximum so far ever in service).

From 1965/6 to 1979/80 every Annual Report contains a reference noting the "continuing slow growth in electricity demand" (1968/9), or "the growth rate of electricity demand continues to be somewhat slower than the historical long term trend" (1969/70). Part of this was out of the hands of the CEGB: in 1965/6 the government reduced its economic growth expectation from the NEDC target of 4% to 3.8% and if electricity is taken to be a commodity with an income elasticity greater than unity, basing expansion plan on an exaggerated target would inevitably lead to over-rapid growth estimates. However, despite the experience of demand not meeting its forecast in 1963/64, and the downward revision of the economic growth target, the estimates for power and energy were for compound growth of 8.9% and 9.3% respectively.

By 1966/67 not only was the target economic growth rate still not being met, commercial and industrial activity was severely constrained and natural gas was perceived as a serious competitor. As shown in Table VI.2 the 1971/2 estimate was revised sharply downward. The same process occurred in 1967/8, 1968/9, 1969/70, and, as Table VI.2 shows, the constancy of the five year forecasts continued until the structural break after 1973/4 finally caused some downward shifts in them.

From then until 1979/80 the problem confronting the CEGB is the continued failure of the economy to pick up (and not only the domestic, but also the international economy was predicted to experience only modest recovery). In addition the "massive increases in oil and coal prices which must worsen the competitive position of electricity as an energy source" (1974/5) acted to increase the uncertainty of the future still further, a condition highlighted by the "continuing strong competition from natural gas, particularly in the domestic space and water heating market, and pressure for energy conservation" (1977/78). The 1978 estimates were for a 2% per annum growth in demand in the medium term but by 1979/80 this had been revised to 1% (which shows clearly in Table VI.2).

VI.3.3 The Scenario Approach

The CEGB capacity predictions have a consistently poor record. In part this has been due to reliance on data inputs which were themselves substantially over optimistic (the government/NEDC economic growth target of the mid-1960s) but which the CEGB was in some sense obliged to use; and in part it is due to the inevitable rigidity of econometric forecasts. This is the argument which claims that the econometric forecast should only be relied upon for periods in which no major structural change is anticipated, since the equations do not allow for inclusion of shifting demand, technology or markets. In 1976/7 the CEGB announced that it had begun to make use of "the economic model developed by the London School of Graduate Business Studies" and the major downward revisions of forecasts date from then. It also appears from the 1978/9 Report that the CEGB was using a much broader approach than that of trend extrapolation and econometrics. "The Board ... takes account of factors such as the development of individual industry groups ... the ownership of central heating systems, and energy saving devices. Its forecasts are based on assessments of the development of a wide range of factors which influence energy demand ..." (32).

The implication here is of a move toward greater reliance on the "scenario" approach to long term forecasting, claimed by its advocates to offer the flexibility that econometrics lacks, and to be able to accommodate observed, current structural changes and those predicted in engineering type studies of disaggregated energy markets. The scenario approach was also used to some extent in CEGB evidence to the MMC, and was a very important part of its evidence to the Sizewell B Inquiry.

Chateau and Lapillonne (1978) present a detailed review of the use of scenarios in long term energy demand forecasting, arguing that econometrics is "too rough and aggregated" - essentially that the methods are too rigid to give satisfactory results. Their approach requires total demand to be split up into a set of homogeneous "energy modules" (households defined by income groups; transport by long distance freight, tourism and so on); then technological change at the engineering level is analysed together with the impact of future energy prices, for a view of the modules' future energy needs. Also acting on those needs are two sets of determinants which make up the 'scenario base'. These are direct determinants (number of consumers, energy intensity of their activity/business; political factors determining future technological choices; socioeconomic determinants such as national values and peoples' concept of the future); and indirect determinants (macroeconomic variables such as the rate and structure of economic growth, the level and distribution of income; industrial location patterns; transportation patterns; energy prices). Analysis of these will produce the base of a socioeconomic scenario which will be established by the future international environment, long run trends, public policy (and the "long term orientation of societal development") and energy prices and supply constraints. The future values of some of these determinants cannot be quantified - particularly the "societal development" or lifestyle indicators; and others too complex or uncertain must be specified by assumption. Once internally consistent socioeconomic and energy demand scenarios have been developed the energy demand forecast for each of the modules can be calculated through a simulation model. Thus, an important set of qualitative indicators is incorporated in the writing of the scenario which may involve large volumes of data, but will, in return, permit disaggregation of energy demand and more realistic forecasting. Each scenario can be drawn up to reflect a set of particular views of society's future choices.

Day (1980) also supports the scenario approach arguing that a techno-economic engineering approach at a disaggregated level is more likely to give useful forecasts than an econometric approach which relies on correlations between dependent and independent variables which fitted satisfactorily before 1973/4 but are unlikely to do so now. He also notes that "no single approach to forecasting is satisfactory" (33). Evans and Hope (1984) also argue that "The ... approach of scenario analysis has much to commend it" (34) in that a project may be analysed against a range of alternative scenarios, allowing different judgements on the future to be evaluated. They also point to a "major drawback": the tendency for the central or trend scenario to be considered predominantly, which clearly contradicts the spirit of the approach. Day (1980), in his analysis of future market penetration by electricity uses "an essentially surprise-free macro scenario", although "it is recognised that unknown and radical changes are inevitable over such a long timescale" (35). MacKerron (1984) discussing the CEGB evidence to Sizewell notes that of the five UK economic scenarios developed by the CEGB, "the Inquiry increasingly showed itself to be interested only in the mid-case" (36). He also points out that of the CEGB's three plant-mix backgrounds ('high', 'medium' and 'no-new-nuclear') it is the medium background which is generally thought to be the most likely description of future CEGB investment.

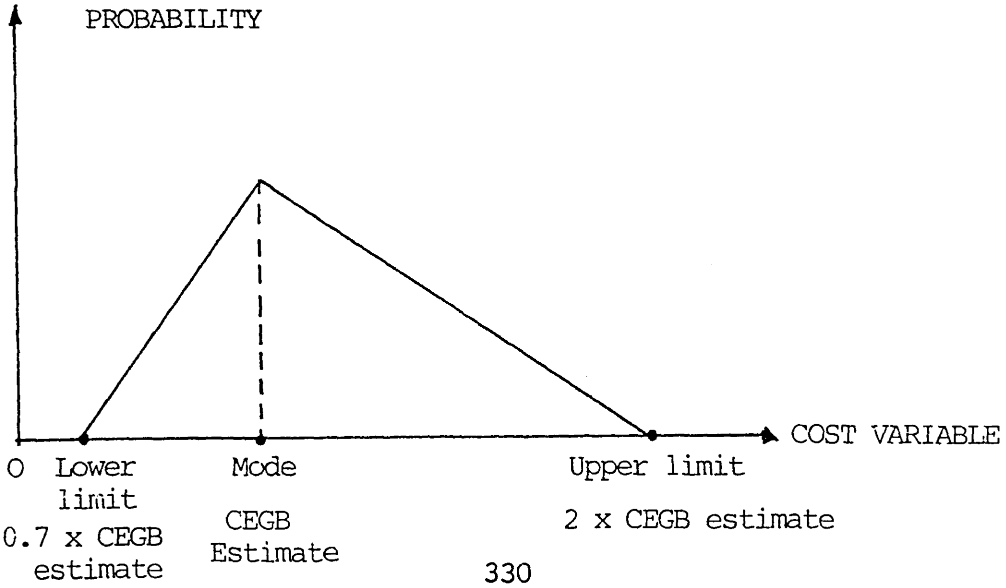
There is clearly a substantial failure of the application of the scenario approach in the examples quoted above and the theory of that approach with its apparent supremacy over econometrics. If, for example, econometrics is to be rejected because it is unable to forecast oil price shocks and then gives terrible forecasts after them because the data are both in short supply and inconsistent, then how will forecasting be improved using an "essentially surprise free macro scenario"? Similarly, Evans and Hope's criticism that the scenario approach fails if users merely take the central scenario as most likely seems to apply strongly to the case of the Sizewell B Inquiry.

Yet in the absence of further information, there is no other rationale for choice since if by "central" is meant "most probable" then that scenario will inevitably dominate the others, even though it has, obviously, a finite (subjective) probability of being wrong. There is evidently a danger of the scenario approach reducing to the simple econometric result of producing a single "best" forecast.

However, Evans and Hope's (1984) analysis restores the scenario approach by examining the specific estimates that go to make up the total cost variable. In each case they accommodate uncertainty by using a probability distribution for the variable rather than a point estimate, (unless the effect of the variable is expected to be too small to alter the outcome). Just as the MMC argued that the CEGB estimate tended to be over-optimistic (see above chapter IV), Evans and Hope accept that these are probably not central. To adjust for this they use 'asymmetric triangular probability distributions whose mode is the CEGB estimate and whose shape implies that the probability of the eventual outcome exceeding the offical estimate is greater than 50% (shown as figure VI.7):

Figure VI.7

Asymmetric Probability Distribtions in Forecasting



Once such probability distributions are established for each cost variable, random samples can be taken and used in their cost minimising linear programming model as many times as deemed necessary to give representative results. The power station which achieves the minimum cost the most number of times will then represent the optimal choice for base load operation. This is not the massively detailed hierarchical scenario approach of Chateau and Lapillonne where probabilistic statements of future events are built in at successive stages and can yield separate scenarios for comparison and discussion. However, the probability distributions (drawn above) can be varied to achieve a similar result.

However, once the methodological reasoning for using the scenario approach is accepted, it is evident that the choice does not, in fact, arise as one between econometrics and scenarios. The Chateau-Lapillonne (1978) model requires a vast amount of data but also some general and probably contentious assumptions on the future course of some (often unquantifiable) variables. But if that volume of information is available econometric models can clearly make use of it to provide as many probabilistic forecasts as decision makers require. A criticism of sensitivity analysis of a central forecast may be that that analysis is insufficiently far-reaching because, typically, too few variables are adjusted and/or the variables are adjusted one at a time and/or the variable adjustment is inadequate. That, in itself, is a critique of how the econometrics is carried out, rather than a critique of the method. The scenario approach and econometric analysis should be regarded as complements in the complex and inexact process of forecasting since the former make explicit the concern with uncertainty and the latter is a proven means of extracting economic information from data. Thus presenting that information (such as elasticities, factor substitutability and so on) within the framework of scenarios bounded by assumptions on uncertainty gives the decision maker as full a picture as possible. Given this approach, the relative roles of the economist and politician in decision-making are discussed later in this chapter (37).

VI.3.4 Forecasting and Nuclear Power Stations

The final element to be discussed in this section on forecasting is the ability of the CEGB to make satisfactory forecasts for an individual or a series of nuclear power stations. Burn (1978) estimated the cost of the AGR programme at £3.8 billion (£ 1975); Henderson (1977) estimated it at £3.2 billion (£ 1975) and again in 1980 Burn (1980) gave figures between £8.7 billion and £11.1 billion (£ 1980). On any of these figures the programme was at least 100% over budget. Rush et al (1977) go further: "it is virtually impossible to ascertain the true economic cost of the AGR programme for that would require knowledge of the stream of past and future costs and benefits not only for the AGRs but also for the alternative programme that would have been built" (38).

Similarly Thomas (1982) states: "overall the (Magnox) programme has failed ... to meet its originally expected operating performance" [although "the programme had a number of objectives and was never regarded as a strictly commercial venture" (39)].

However, the CEGB position is that such views are difficult to maintain: "no single method of computing generation costs can provide a definitive description of the costs or be used to judge past investment decisions. Differing overall economic conditions, changing views of required investment returns, and developments in technology all make comparisons between investments in different periods particularly difficult" (40). And it is undoubtedly true that throughout Europe the complexity of nuclear projects was generally not appreciated and growth rates led to expenditures well above budget, (see Manners (1980)). For the case of the United States, Freeman (1983) (managing director of the Tennessee Valley Authority) states: "we went too far too fast in deploying a reactor type we knew too little about. It is also fairly clear that we moved too quickly to capture perceived economies of scale. Utility executives were ordering reactors in the 800 MW to 1300 MW range at a time when their only operating experience was with 180 MW reactors" (41).

Sweet (1983b) also claims that in their attempt to expand their nuclear power base as quickly as possible the French were forced to learn "on the production line", which, in his view, represented a possibility of a decline in safety standards. These points - the over-rapid attempt to scale up LWRs in the USA and development with incomplete information in France - represent precisely the major, basic criticisms of the AGR programme in the UK: "the surprising aspect of the 1965 decision was the size of the government's commitment to technology which was unproven on a commercial scale" (42). That decision meant that construction of more than 6000 MW of AGR plant had been started by 1970, yet there was no commercial scale prototype anywhere near completion.

Keck (1980) in reviewing the decision-making process that led to the West German Fast Breeder development, makes it clear that initial choices by the government were guided more by political expediency than by the more commercial judgements of the manufacturers; by the time that experience had taught the government officials to take a more realistic view, the programme had developed a momentum of its own which, to some extent, prevented any proper re-evaluation of the direction it was taking. As a particular example, Keck notes that the West German government wanted some return on its contribution to Euratom (both political decisions) and so backed the FBR development without a full economic analysis and despite reluctance from advisors. Thus the political decisions determined what should have been an economic decision.

Hellman and Hellman (1983) analysing the USA experience conclude that nuclear power to date has largely been a failure due to the "very wide gap ... between the design and actual performance of nuclear power units" (43). They discuss the court case between Portland General Electric Company and Bechtel Corporation (finally settled in 1981) in which the former were attempting to recover unexpected cost increases in plant supplied by the latter. From this arose what they refer to as the "Bechtel Theorem". Bechtel argued that the construction and development risks for nuclear stations were "extraordinarily variable, unpredictable and uncontrollable" and were the responsibility of the purchaser not the supplier. Hellman and Hellman feel this position (which Bechtel argues applied from 1968) meant nuclear power costs were then, and have been ever since, "unpredictable and uncontrollable" (44).

VI.3.5 Capital Intensity and Inflexibility

In considering what has been learnt from nuclear power decisions so far, Collingridge (1984 a and b) argues that nuclear technology is one which is highly vulnerable to forecasting error so that mistakes may be expected. The problems are that such mistakes will be peculiarly expensive because of the nature of nuclear power; furthermore, it may also be impossible to react to the realisation that mistakes have been made as the learning time is so great that development may be too advanced to be halted or redirected. As has been argued above, forecasting in this area has a generally poor record, which deteriorates as the period being forecast grows. Nuclear plants may be thought of as having a lead time of at least five years (the Magnox plants were planned to be built in four years, but all took two to three years longer; the disastrous AGR programme cannot be considered to be representative); this means that operating data will not start to become available until the sixth or seventh year of the development and such initial data may be expected to be unreliable. If a series of plants is coming on stream successively then data will build up, but the learning time must inevitably be very slow. Moreover, the data will probably be biased. It is likely that the first reactors in a series will be the least successful in terms of construction and operating costs; later reactors should benefit from mistakes (as in any large project). Of course, if the initial, limited and slowly-accumulating operating data are themselves used to forecast future experience, the programme could well be halted and possible benefits will never accrue.

The great capital intensity and hence inflexibility of nuclear power plants implies that when the inevitable mistakes occur, they are going to do so at very high cost. If the forecasts on which a nuclear programme was based are found to be in error, the capital already sunk in construction is non-retrievable; thus, the programme may well be continued, despite knowledge of the erroneous basis. This process is not limited to nuclear power decisions, but is a feature of untried and advanced capital-intensive technology. Defence contracts such as those for Trident or Nimrod regularly overshoot the initial budget estimates by substantial margins. Yet the projects often continue because having spent so much already on R and D, completion of the project will cost comparatively little money. The previous capital expenditure cannot be reclaimed and is in that sense irrelevant; but the project can be made viable with limited further funds. Similarly, in the case of nuclear power, investment decisions become irreversible once funds have been sunk in them. The capital-intensity and single-purpose of nuclear stations act to underline this. It is also suggested that, once started, the growth of the nuclear industry becomes continuous. Widdicombe (1980) argues that the front end of the fuel cycle must be developed to service the new reactors; and as thermal reactors produce plutonium which may be used in FBRs, and storage of spent thermal fuel is moderately difficult, expensive and wasteful, so the arguments for further back end of the cycle projects and FBR construction are strengthened. In this way each development prepares the ground for the next, provides more employees, construction, research teams all of which demand protection. Hence, not only is an initial wrong decision expensive in itself, it has the power to lead to an inexorable series of investments all of a similar nature.

Collingridge's other major point on governments' investment problems in nuclear power lies in the difficulty inherent in choosing how to develop a programme of reactors. He contrasts "serial" and "piecemeal" ordering; the former is represented by a decision to undertake simultaneous construction of a series of reactors, to come on stream sequentially. Its advantages are that as the benefits of cheap power are felt, those benefits are quickly multiplied as successive reactors are commissioned. Second, if the design is consistent then the constructors' and operators' learning curves should show substantial and fairly rapid returns. The disadvantage is that if forecasts which provided the rationale for the programme are shown to be wrong, then, because serial ordering generates a large volume of plants under construction simultaneously, the sunk capital may be so large as to produce the result discussed above: continuation of the programme in the face of knowledge that it is based on mistaken premises.

Piecemeal ordering involves a sequence of construction, learning, further construction. Its advantage is that if the initial construction is deemed mistaken, re-orientation or cancellation of the notional programme is simple (and costs prospective, not actual, employment). The drawbacks are that the benefits of a successful initial reactor may not be multiplied for some time since construction of a second has not been sanctioned. Also, the learning experience generated by a single reactor is very severely limited: data accumulate very slowly and, because the reactor is by definition unique, it is impossible to tell whether the data are giving an accurate picture of the performance of the reactor type.

When attempting the appraisal of the economic role of a particular reactor, nuclear power presents specific difficulties. It is a capital intensive technology with a long lead time and so requires accurate forecasts both of the market it is to serve and of its own operating characteristics. The former forecasts - of periods up to thirty years - are simply not available with the necessary degree of accuracy for them to be a sufficient basis on which to make decisions. Econometric analysis within contrasting scenarios provides the decision framework but can only guide, not decide. The forecasts of reactor operating experience can only become firm when based on actual operating data from commercial sized reactors. But even with serial ordering such data are slow to accumulate and initially , are quite likely to be incommensurate with data that would be derived from a settled system. However, whether or not this is the case cannot be known, and, hence, forecasts using the new data are possibly wrong and certainly have a meaning which is hard to identify (45).

Serial ordering risks multiplication of the losses resulting from a mistaken original decision; piecemeal ordering risks delaying benefits arising from a correct decision. In either case, once the project is under construction, its capital intensity and inflexibility will imply that it should continue even under severely adverse conditions as cancellation would prove even more expensive and redirection impossible. Once built, the economics of the reactors dictates that they should be used for base load operation - the capital costs are byegones and the reactors are fuel-cheap. This produces two further biases. First, current operating experience cannot be used as the basis for a future SCBA, unless there is major system replication. Second, running the new reactors on base load squeezes the total base load available for either conventional stations or the next generation of nuclear plant and so prejudices the case in favour of either of them.

These difficulties are not unique to nuclear power; the similar example of defence procurement was noted above and any capital-intensive long duration project based on the latest technological and scientific research will fall into the same investment class. The structure of this section has been designed to give weight to the argument that while economic analysis provides essential - and valid - guidance for such decisions, it cannot be expected to be able to make those decisions alone.

The French nuclear development, based originally on gas-graphite reactors but achieving its big growth and success with LWRs is described by Collingridge (1984b) as "ill-informed and arbitrary" (46). He argues that EDF were involved as much in politics (ousting CEA from its central authority) as in rational decision-making and pushed for LWRs on that basis. The serial ordering multiplied possible risks and created a large manufacturing base, which must soon face excess capacity, unless export orders can be found to replace an inevitable decline in domestic construction. The same large manufacturing ability will, however, be needed again in the comparatively near future to build replacement reactors, implying a clear possibility of a strong cyclical movement in the supply industries. There still remain two further risks for the French programme: since the benefits will accrue over twenty to thirty years, it may become apparent that an alternative energy programme would have proved superior to this highly specific (and inflexible) approach. And should a generic fault be found in the French reactor there could be a very expensive period of imported power while all were checked.

The achievement of the French nuclear development to date is attributed chiefly by Collingridge to the centralised decision making process. This is echoed both by Starr and Braun (1984) and by Weinberg (1984) who argue that, in contrast, in the very decentralised even fragmented market experience of the USA, with its diversity of owners, constructors and architects, the opportunity for a useful learning curve to develop has been severely curtailed. The low cost construction that typifies the French experience (one buyer and one constructor, and, comparatively much less stringent regulation, leading, uniquely, to declining capital costs (47)), has, thus, not been achieved in the USA.

The same conclusion is drawn from an equivalent comparison by Freeman (1983). He discusses the implication of the major backfitting programme being carried out on LWRs in the USA - the programme is so expensive that many utilities have dismissed a future nuclear option; and "in a sense no nuclear plant is built yet" (48) because of this continual backfitting and "patching-up". In Canada, Ontario Hydro has replicated the same design CANDU plants and have thus gained the benefits of both a very successful design and of standardisation.

The British AGR programme was a clear example of non-standardisation; the first three reactors being, effectively, three different variations on a theme. Since there was no commercial sized example as a model, the substantial delays were the inevitable result of modifications to design and attempts to solve continual, unpredicted technical difficulties. The opportunities for centralisation of planning and construction were not taken; instead the three large consortia were offered protection under the guise of maintaining competition (49). However, there is evidence that once replication and closer, more centralised control are introduced this reactor construction programme can become substantially respectable. Bindon (1984) discusses these planning changes in the case of the Heysham II station which replicates Hinkley Point B except for enhanced safety and obvious construction improvement changes. It appears that both Heysham II and Torness are meeting construction targets (50).

VI.3.6 Forecasting and Decision Making

The conclusion of the forecasting section is that high-technology, durable, capital-intensive investment projects make demands on forecasters at both the macro- and micro- (disaggregated) levels which cannot be satisfactorily met. Collingridge (1984a) argues that blame cannot be placed on the forecasters, but rather on the technology that requires such forecasts. At the macro level, estimates of price trends in coal or uranium, of consumer demand for electricity, of power station position in the CEGB merit order, all in twenty five years' time are, given experience of success of such estimates over five or six years, of little practical value. Re-estimating such trends within a scenario framework will permit a broader perspective and give a greater weight to the overriding significance of uncertainty. But as Evans and Hope (1984) point out, it is doubtful whether any form of forecasting methodology could have produced "investment plans which remained robust in the wake of the first oil price rise" (51).

At the micro level, power station construction and operation data accumulate very slowly with, initially, an unknown bias. Walske (1984) argues that for nuclear power to become a viable base for new capacity in the USA "ways must be found to decrease the uncertainties and financial risks associated with capital-intensive and long lead time construction" (52). These uncertainties and risks are generic to this class of technology; moreover, such technological development, once commenced, builds its own momentum based on the substantial sunk costs that its capital intensity creates. Possibility of cancellation in the light of changed information is small as the capital expenditure cannot be retrieved, and the project completion may be realised for comparatively limited further cost (no matter how much over initial budget the project may be at that point). Centralisation and standardisation of planning, purchasing and construction appear to have led to clear economies in France and Canada and are recommended by several authors for the USA and the UK. That approach, however, implies "serial ordering", the disadvantage of which is that, should an error have been made, its cost is multiplied by the number of stations simultaneously at various stages of construction. The planner's dilemma is that the alternative of "piecemeal ordering" carries the drawback that programme benefits will be delayed by the much slower construction and commissioning of stations.

Despite these reservations, forecasting remains an essential element of a SCBA of nuclear power. Energy supply, it has been argued, is a relevant part of the analysis and decision making on how to produce the electricity deemed likely to be demanded as part of that overall supply requires scenario forecasting at both macro economic and disaggregated levels. The implication of the reservations is that when dealing with the degree of uncertainty inherent in these calculations, care should be taken to ensure that the results are not called upon to give concrete and absolute answers. They can only guide and not decide.

VI.4 INTANGIBLE COSTS AND BENEFITS

VI.4.1 The Damage Function

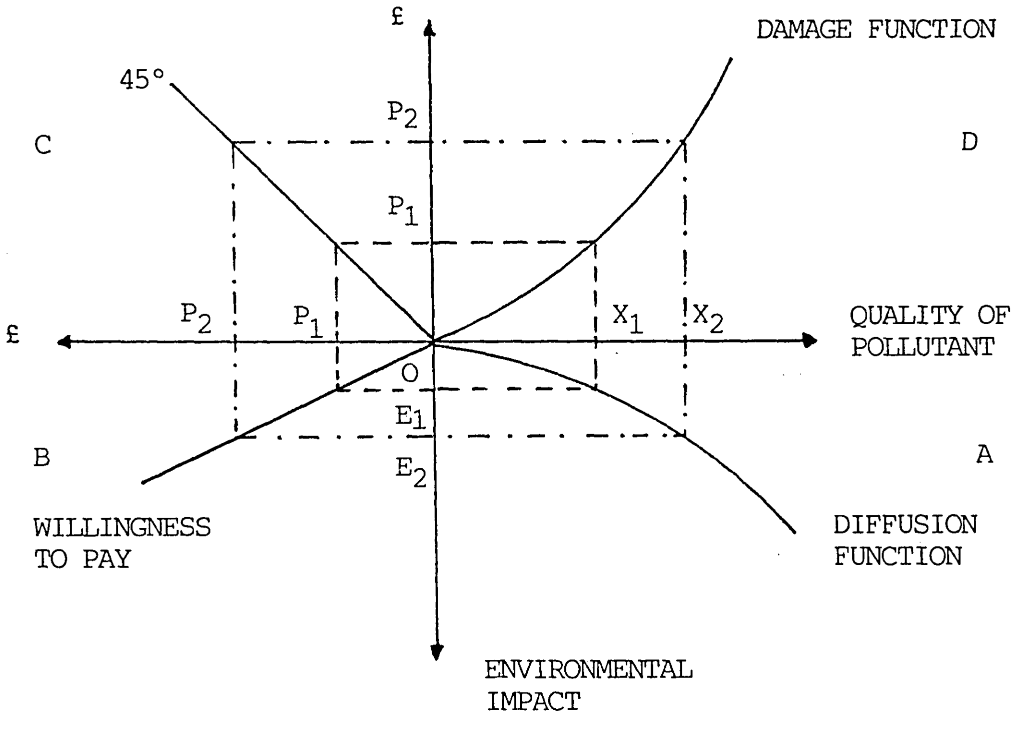
A central feature of any SCBA is its attempt to identify and measure the unpriced effects of the project under consideration. It is entirely probable that this will cause economists to ask questions to which "they are not yet able to provide the correct answers" (53). Yet it is also the case that unless such effects are investigated, albeit imprecisely, the wrong set of prices for electricity will be established, hence the wrong incentives for consumption (domestic, commercial and industrial) and a sub-optimal energy mix will result.

The problem in this section is to define the particular environmental and health impacts that might be associated with electricity production generally and with nuclear power in particular, and to establish how far economic evaluation of these can lead to adequate quantification. the areas for consideration are property damage, climatic change, human health, pollution and general social effects. The USAEC (1974) study in its general discussion on costs concludes that the sum of those mentioned above is small in comparison to the 'conventional' energy costs (production costs) and questions of electricity supply are more likely to be dominated by ultimate fuel resource availability than environmental considerations. However, Ramsey (1979) argues that the relevant data are subject to such great uncertainty that unequivocal, exact decisions are impossible. The validity of the latter view is shown by Sors (1981) who, in discussing the problems of monitoring pollution writes "one does not in general know where, when, how and what to monitor" (54). Thus, while it may be the case that certain effects are believed to be caused by power station operation, the precise casual chain is not known, nor is it at all obvious how to distinguish that chain and further side effects. This problem is exacerbated when cause and effect are separated both spatially and temporally.

A standard economic approach to the problem would require some quantification of two analytical elements. In figure VI.8 quadrant A shows the "diffusion function": this relates the quantity of a pollutant to its effect on the environment. Its precise shape is not important here, but it is drawn to show impact increasing exponentially as the pollution increases. Quadrant B shows society's willingness to pay to avoid each level of damage to the environment and, simply, the worse the impact, the more society will be prepared to pay. Quadrant C is a mapping quadrant.

Figure VI.8

The Damage Function

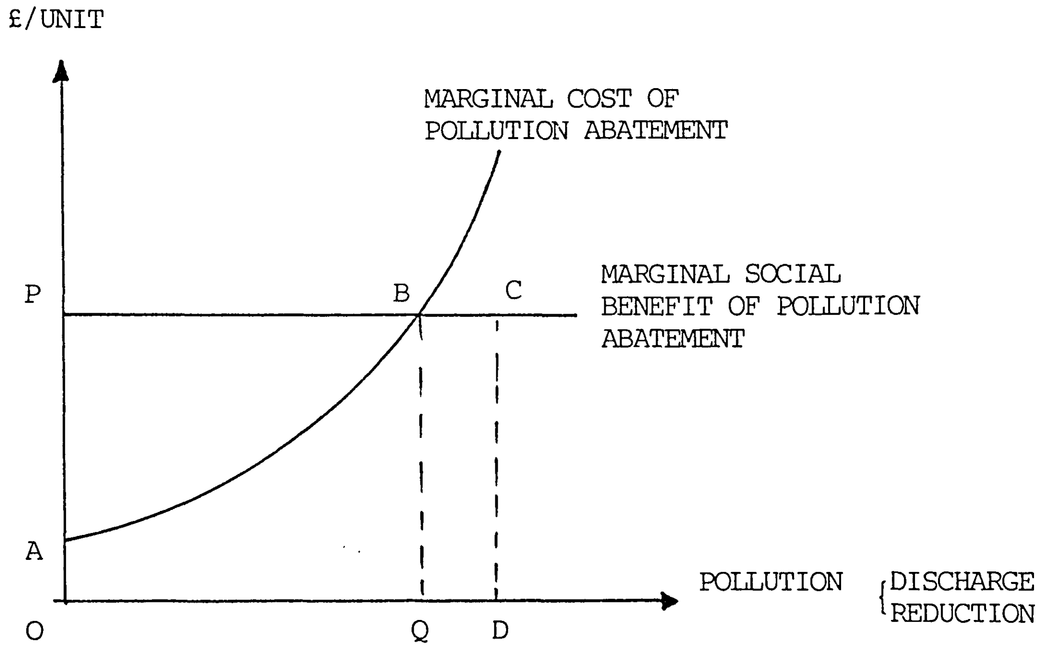


The damage function of quadrant D may now be derived. A quantity OX_1 of the pollutant causes an environmental impact of OE_1 - this is some measure of the quantity of services previously provided by the environment and now degraded by the pollutant; (relative cleanliness of air or water; ability to absorb waste and so on). The impact of OE_1 is deleterious and society would be willing to pay £OP_1 to avoid it (either as a bribe to the producer to cause internalisation of the unpriced effect or directly in purchase of abatement equipment - or not at all; this may be a purely notional willingness to pay). Mapping these points to quadrant D and repeating for a pollution level OX_2 produces society's damage function: the cost that society associates with each level of output of this particular pollutant.

The analysis has now established society's evaluation of pollution and hence it is possible in figure VI.8 to draw the 'marginal social benefit of pollution reduction' curve. For simplicity this is drawn as a horizontal line, although the theory implies that it would be downward sloping. The marginal cost of pollution reduction curve is upward sloping - the marginal cost of incremental waste reduction will necessarily rise.

Figure VI.9

Marginal Social Costs and Benefits of Pollution Reduction



With the information shown in figure VI.9 the government sets a pollution charge of £OP/unit (for example, per tonne of SO_2 removed from the flue gas of a coal fired power station). In that case the ESI would choose to install flue gas scrubbers (or equivalent technology) to clean up the first OQ tonnes of SO_2 since the total cost of so doing would be £OABQ whereas the tax imposed on uncleaned stack gas would amount to £OPBQ. Beyond OQ tonnes it is cheaper for the ESI to allow the pollution to go uncleaned as the marginal cost of abatement is greater than the pollution charge. Since the latter is equal to society's marginal benefit of pollution reduction, this is also the social optimum. Additional uncleaned pollution up to OD would cost the ESI £QBCD in charges - which is the compensation required by society for the damage (given the horizontal MSB curve). In this approach the government has taken what was previously a common property resource - the air (or air quality) - and established property rights over it. Economic theory predicts that common pool resources will be abused; in this example since no one owns the atmosphere, any manufacturer can use it to dump waste and so degrade the quality of the air. Creating and enforcing property rights leads to the socially optimal level of pollution, since the right to dump waste in the atmosphere now resides with the government which is prepared to sell the right at £OP/unit.

VI.4.2 Cost Estimates for Health and Environmental Impacts

The application of this approach requires information on both the diffusion function and on society's damage function (the monetary evaluation of unpriced effects of the production of electricity); unless the former can be established, measuring the damage function becomes even more open to criticism. Hence, environmental monitoring and surveillance is essential, ("perhaps the most important scientific tool in the management of pollutants already in the environment" (55)); yet the necessary prior information on environmental processes is often not available. Moreover the health effects of different pollutant concentrations and exposure are inevitably complex and pose substantial difficulties for the design of monitoring and evaluation systems. An example of this would be the question of whether or not a threshold exists for a particular pollutant, below which concentration level damage may be assumed not to occur. This threshold would then represent an ambient standard for emission of the pollutant and would be formally equivalent to the pollution charge in the model above (since it represents not a price control which determines quantity but a quantity control which determines expenditure on pollution control equipment). Such a threshold has become "generally accepted for the classical air pollutants such as SO_2, NO_x, CO" and so on (56). However in the case of nuclear power, radiation is taken to have no threshold effect, and instead a linear dose-response relationship is assumed. This implies that it is valid to take data on the response to high dose rates (from medical use of X-rays for example) and then extrapolate back linearly to derive the low dose-response relationship. This approach is used because of the formidable and possibly insuperable statistical difficulties inherent in attempting to analyse low dose effects. Apart from the problems of isolating the radiation due to power stations from the natural background and of estimating causal relationships with mortality and morbidity, the sample size would need to be very large before any statistically significant results could be claimed. If a threshold effect did apply in this case, failure to use it implies the imposition of an unnecessary cost burden on the nuclear industry; in the absence of definite information the use of the linear relationship is a risk-averse response and is a form of insurance premium paid by society to guarantee safety.

Analysis of the diffusion function is further complicated by persistance effects (a pollutant emitted at acceptable levels may build up to a dangerous level if it does not degrade over time), and by synergistic effects as a set of pollutants combines to produce an overall effect worse than the sum of the parts. There is also a bureaucratic problem in that many different government and local authority departments and separate institutions are collecting and analysing data so that the task of collating all the material becomes immense (and prohibitively expensive). Nevertheless, the research must be continued. Sors (1981) quotes the 1979 UK Central Directorate on Environmental Pollution: "The effects of these long term low dose exposures are inevitably very difficult to attribute to individual pollutants ... precise scientific assessment will not always be possible ... a careful assessment of costs - not only of preventative or remedial measures but also of environmental damage - is essential" (57).

The difficulties inherent in attempting to follow this advice on the necessity of assessing costs are no less than those of defining the diffusion function. Air pollution threatens health (as well as crops, buildings and so on) but just as with the radiation example, the severity of the impact is difficult to determine and health effect estimates will fall into a wide range and as Ramsey (1979) says " end up as less than totally convincing" (58). Highton and Webb (1981b) discuss pollution abatement costs in the ESI and note that " a 2000 MW station burning coal with an average sulphur content of approximately 1.5% would emit 130,000 tonnes of SO_2 and 10 million tonnes of CO_2 per annum" (59) (assuming a 60% load factor). Less nuclear power would in the immediate future mean burning more coal and, hence, increasing these pollutant outputs (and NO_x emissions - Ramsey (1979) states that for the USA in 1972 16% of all NO_x emissions were estimated to come from coal fired power stations). The indirect financial costs of the environmental impact of these pollutants must then be assessed. Gaines et al (1979) assume property damage is directly proportional to the quantity of fuel used per year and so adjust the cost of producing electricity for this effect by adding an annual increment to the cost of fuel. Ramsey (1979) quotes estimates of the cost of property damage for every new 1 GW coal fired station lying between $700,000 and $7 million per annum. This huge range clearly implies substantial uncertainty.

Similarly the CO_2 and waste heat emissions may as Flowers (1976) notes have severe climatic effects but there is, again, great uncertainty. The CO_2 may cause the "greenhouse effect", but that effect itself is not agreed, nor is it certain that the observed growth in CO_2 in the upper atmosphere is primarily caused by burning fossil fuels (as changing agriculture and deforestation may also be significant). Gaines et al (1979) regard the impact of increased waste heat on the environment as a phenomenon too inadequately understood to be quantified and so take no account of it in their analysis. The SO_2 emissions are generally agreed to result in acid rain (60); but there is no international agreement on the effects that the acid rain has on major environmental features such as forests and lakes.

Both Sors (1981) and Ramsey (1979) argue that despite the lack of scientific accord and the current inadequacy of the data, the possibility of environmental disaster is sufficient to require policy makers to act nevertheless. Ramsey argues that "in the absence of ... a balanced decision, the worst danger is that no decision at all will be made ... the best choice for society has to be to provide for more than than less in selecting mitigation procedures" (61). This last point (already arguably in operation for radiation release control in nuclear stations) is a major element in Ramsey's overall conclusion. The data are poor and the health and environmental impacts very uncertain; accordingly the theoretical optimum of equating at the margin the costs and benefits of pollution abatement is a distant prospect. In his view it is preferable to spend more than may appear necessary on abatement to guarantee future safety - the insurance premium argument - and avoid the possibility of environmental catastrophe.

The remaining intangible effect of specific relevance to a SCBA of nuclear power is the view that the growth of such a technology is harmful to the social fabric - a view expressed in Lovins (1977), and by Friends of the Earth at the Windscale and Sizewell B Inquiries. The argument is not limited to nuclear power but refers to all large-scale, complex (hard) technologies. These are seen as leading to greater centralisation and control of society, an elite group of technocrats, increased bureaucracy and, in the nuclear case, armed police and limitation of civil liberties. Large scale technology of this kind requires government intervention, huge expenditure and imposes risks which no one in society may avoid. Once undertaken it begins to determine the demand for electricity by imposing its growth on society. The development of the Green movement in continental

Europe, and their success in using the licensing system in West Germany to delay the nuclear programme substantially, is evidence of the power of views of this kind. Nuclear technology is the particular focus as it is so complex and more likely to lead to centralisation of control and technology.

Clearly these political views (representative of conflicts of values which it may be impossible to resolve) must find their outlet in the normal democratic process and with the fullest provision of information; (the following section on planning looks at this point), but it should be noted that while large scale hard technology may have a coercive effect on social development, small scale technology may similarly operate to coerce people against their will (62). Also Manners (1980) notes "the occasional unwillingness of the (nuclear) industry to admit openly and fully to the problems [of safety]" (63); such a reclusive attitude to information can serve only to strengthen both opposition and the belief in centralised decisions being forced on society.

VI.4.3 Policy Implications of Valuing Intangibles

In his summary of the evaluation of intangible costs and benefits in electricity supply, Ramsey (1979) lists four "value orientations" - preservation of health, protection of the environment, avoidance of catastrophe and equity - and compares the relative impact of coal and nuclear stations on them. Clearly there are many intangible effects which are common to both systems (valuation of loss of life or morbidity, loss of scenic amenity, land use by the industry) but this section has attempted to point to those of specific relevance to nuclear power. Ramsey's conclusion is that the data are inadequate to support a clear decision in favour of one power system over the other, so the safest solution is to maintain both systems.

The economic theory of external effects presents the means of creating the optimal level of pollution for society by equating the marginal cost of control with the marginal social benefit derived from an incrementally cleaner environment. But the analysis of the diffusion and impact of pollutants in the environment remains limited and generally without firm conclusion - that is, knowledge of the "damage function" remains vague and ill-defined. Consequently any attempts to place monetary values on damage suffered must be, to some extent, arbitrary and will involve value judgement in the face of great uncertainty. However, some attempt must be made within a SCBA to make these judgements and hence to see how sensitive the investment appraisal is to them, even if the range of each estimate may be extremely wide.

VI.5 THE PLANNING INQUIRY SYSTEM

VI.5.1 The Problems Faced by Planning Inquiries

On 12 December 1979 the then Secretary of State for Energy, Mr David Howell announced the need for a new nuclear power programme: "even with full exploitation of coal and conservation and with great efforts on renewable energy sources, it would be difficult if not impossible to meet this country's long term needs without a sizeable contribution from nuclear power ... subject to the necessary consents and safety clearances, the PWR should be the next nuclear power station order" (64). This establishes a particular public process: the decision in favour of a PWR has been made, (Brett-Crowther (1980) writes: "the big decisions of cost-benefit risk analysis seem to be secretly debated within government circles" (65)). Questions of (local) public interest may then be raised at the local Planning Inquiry required to give the "necessary consents". In many ways the Planning Inquiry has become the only substitute for a true SCBA; it has certainly changed its own nature. Wynne (1980) notes that the 1958 Trawsfynydd Inquiry took three days with the major item of debate being the impact on the landscape. The 1974 Torness Inquiry took seven days, the 1977 Windscale Inqury took one hundred days, and the 1985 Sizewell B Inquiry lasted 340 days. The "Flowers Report" (Flowers (1976)) recommended that all major nuclear projects should be decided by explicit political process, and objectors' cases at both Windscale and Sizewell have clearly politicised the energy supply issue (66).

Both Windscale and Sizewell took the form of a judicial inquiry, an approach which permits submission of evidence from any interested party but which appears to limit the political element in favour of a legalistic, fact-finding attitude. This leads to the criticism that the Inquiries have attempted the impossible: to analyse the factual content of the disparate arguments and reach an objective and definitive solution. Thus Wynne (1980) writes that "In complex technopolitical areas, such as nuclear matters, it is impossible to have a "conclusive debate" (67), and Greenhalgh (1984) argues that in the areas both of economic forecasting and safety analysis unresolved issues are essentially matters of judgement. They are not matters of economic, accounting or scientific fact to be elicited by a legalistic inquiry devoted to discovering a factual and definitive conclusion.

It must be remembered that the Inquiry remains an advisory body; the outcome of the proceedings in the form of the Inspector's report will recommend a particular decision but it is the Minister who is charged with making that decision. Despite the sheer size of the Sizewell B Inquiry, and its unusual procedural characteristics which have "far outgrown those of the standard public local inquiry" (68), this remains the case despite public perception to the contrary (69). Moreover the Inquiry system has increasingly had to deal with major projects having significant national policy implications, and representing remarkably complex technical and social issues. Yet it is not evident that the system has been able to cope with the new demands made on it. Pearce et al (1979) argued that the objectors' cases were disadvantaged in that they had no access to the finance of the proponents of the nuclear developments, frequently insufficient time even to attend the Inquiry and faced difficulties in dealing with the information that the proceeding generated, (the latter being a particularly formidable problem in the case of Sizewell B).

Despite the Inspector's "continual concern to ensure that the proceedings are full fair and thorough" (70) these criticisms still hold. Greenhalgh (1984) argues that the government is using the Inquiry system because it wishes to see greater public participation in decisions on advanced technology and to respond to public concern over safety and dislike of the increasing centralisation of control that such technology is believed to represent. A favourable decision will thus legitimise the PWR proposal of December 1979. However, he concludes that objectors will not be satisfied with a decision contrary to their wishes and the vast scale and detail of the Inquiry has not contributed to public knowledge (71).

Wynne (1980) goes further, arguing that the Inquiry is serving as a "ritual trial or public ordeal" (72) which airs conflicts of "facts" but does not resolve the underlying conflicts of values. By creating a trial-type procedure the Inquiry "filters out" the broad political arguments but runs into extensive and esoteric technical arguments which may exclude most objectors on grounds of competence but which may anyway have no definitive conclusion. Wynne also argues that the Inquiry framework will tend to reinforce the technocratic position despite the fact that large scale modern technology is often developed with government support and intervention. Brett-Crowther (1980b)also feels that the Inquiry is a means of imposing the decisions arrived at secretly within the government.

VI.5.2 Improvements to the System

The Planning Inquiry system, allowed to have both new procedural characteristics and greatly increased time, broadened in the scope of arguments which may be accepted as relevant is nevertheless subject to continual criticism. At one extreme the Inquiry is seen as an immensely expensive ritual designed to sanction a decision already made and to "factualise" what would otherwise be political decisions. A rather kinder view of the process is that while it permits debate it is unable to perform the function it is designed for - to reach a definitive conclusion - since no such conclusion exists. In consequence the "upgraded" planning inquiry cannot serve its original purpose of dealing with specifically local issues as it is overwhelmed by national concerns.

Owens (1981) quotes the Outer Circle Policy Unit (1979) solution of submitting major projects to an Inquiry before any planning application. This Inquiry then considers the principle of the project - in effect this would be the point for a SCBA - and if approved the local planning inquiry can revert to its original purpose.

Pearce et al (1979) argue strongly for nuclear power to be an issue on the "national agenda" and suggest an Energy Policy Commission as an organisation specifically designed to review all aspects of policy. Both suggestions would permit the application of a true SCBA and the dissemination of information. They would also permit local planning inquiries to deal with local issues. Furthermore, to the extent that the debate is really about the structure of society and the role of technology the political debate can revert to Parliament where pressure groups can exert the political influence from which they are largely diverted by the Planning Inquiry. The debate on the desirability of growth, of hard technology can usefully take place where it belongs.

VI.6 SOCIAL COST BENEFIT ANALYSIS AND POLICY

VI.6.1 The Market Alternative

The forecasting record of both "the" nuclear industry and the government, the accuracy of economic assessment and investment appraisal, and the inevitable continuing uncertainty about future energy policy, all imply a central role for SCBA in helping form that policy.

Seneca and Taussig (1984) believe SCBA to be "the unique contribution of economics to the solution of social problems ... indispensable to the proper conception of these problems ... [and] a problem-solving tool" (73). Unless policy is formulated within a framework which attempts to ask the right questions about forecast accuracy and sensitivity, scenario plausibility, social cost evaluation and how to accommodate time in the analysis, it will be partial, ad hoc, and open to continual criticism. It is true that the empirical basis for providing satisfactory answers to these questions is often narrow and the uncertainty extremely difficult to deal with within reasonably close intervals, yet knowledge is growing and an imperfect analysis must be a better guide to policy making than none at all.

However, in the light of past government failure in forming satisfactory economic evaluations for policy, an entirely different approach could be recommended. That is to use the market mechanism to make the decisions. Weinberg (1984), and Starr and Braun (1984) argue that the centralised (non-market) approach of the French government using EDF to develop nuclear power alone was the basic reason for its success. Fowler (1983) believes that "the market place does not deal well with the future" (74) since it compiles and summarises the forecasts of all individuals - but such forecasts may be wrong or biased and will, anyway, not include the views of those with limited or no economic power (children and unborn generations) who will be affected by the impacts of today's decisions. In his view the market can only deal with the short term. However, Henderson (1981) and Keck (1980) both argue that it is precisely these views which have led to such poor centralised decision making (Henderson refers to the UK, Keck to F.R. Germany). Henderson points to a consistent UK government attitude that nuclear power decisions are "strategic" and must, therefore, be taken within the Cabinet, or perhaps the Department of Energy; to this view is allied the preference for using monopoly bodies such as the UKAEA as instruments for implementing the policy. Hence, Henderson sees a high degree of centralisation in UK decisions (as Keck does for F.R.Germany).

In the BBC Radio 3 Reith lectures of 1985 Henderson developed a powerful criticism of what he referred to as "do-it-yourself economics" at government level: his position being that many policy decisions are based on policy-makers' economic beliefs which have no foundation in theory. (Energy self-sufficiency because imports are "bad" being an example). His 1981 article has much of this attitude in it as Henderson presents the policy formation process as essentially "pre-economic" in that it persistently fails to consider marginal costs and benefits. Hence, he believes that part of this process is the central view that Britain has a technological edge in nuclear power which is good in itself and for the balance of payments. Therefore a strong, viable nuclear industry should be maintained. As part of a general view on the nuclear element in providing overall energy needs this position is virtually invulnerable, despite the knowledge of how costly mistakes have been. The solution is to decentralise the decisions to the market and (subject, naturally, to government regulation on safety and the environment) allow competition to determine the growth rate of nuclear power and the structure of the industry. The more that private firms are required to make commitments of their own financial resources, the more likely they are to produce realistic assessments of the relevant marginal costs and benefits.

The short-term nature of market behaviour (mentioned above) is also open to criticism. An Austrian view of the market would be that it is a continuous process, moving toward but never achieving equilibrium, but also using, efficiently, all avilable information. It is not, therefore, possible to improve on the outcome it generates, if for no other reason than that the sheer volume of information it handles could not conceivably be artificially processed. Moreover, the State is not endowed with some special wisdom that implies it can satisfactorily enter markets and operate successfully. Private businesses avoid bankruptcy if they can move with the market - part of their business knowledge is tied up in that expertise. The State is not a body which can (or should) attempt a similar activity. The beauty of the market is that individuals need not know how it works, but merely respond to its signals; in doing so they create the next set of signals and the behavioural incentives. Mistakes are costly and people will try to avoid them and learn from them when they do occur. Imposing decisions on the free market system will distort its price mechanism and misallocate resources.

This, of course, is essentially an ideological debate. In practice the experience of nuclear development in the much more market-oriented framework of the USA does not provide evidence for the superiority of the market (75). Benn (1984) claims that market forces alone have never caused the development of nuclear power anywhere in the world, nor has private capital completely paid for that development. Collingridge (1984a) points to the early stages of PWR/BWR development in the USA where wildly overoptimistic forecasts on capital costs and loads led to cost cutting and huge losses.

Although the market remains a possible solution to the energy policy-making problem it is not a likely proposition for the UK. Even if it were to be encouraged the UK energy market has features which make it undesirable - many of the sectors are monopolistic and are making decisions interdependently. Short term decisions are quite likely which could mean that if nuclear power is currently "unpopular" its development is halted. But that could lead to a dispersal of the necessary manufacturing infrastructure and technical knowledge so precluding possible future growth (except at substantial expense).

The latter point is of particular significance in the development of the whole nuclear sector. Wynne (1980) argues that by its nature big technology requires long term commitments that become fixed and very difficult to adjust or reverse. But the opposite is also argued: a decision not to go ahead now with a new nuclear station does not imply that a possible favourable decision may be considered in the future. As has been discussed above and in Chapter IV, without orders the manufacturing and design base may disappear. The 'no' decision is substantially more significant than it may appear. Evans and Hope (1984) argue the case for an 'enabling decision' on these grounds. They feel that (at least) one PWR should be constructed not on grounds of offering low cost electricity but on the grounds that the nuclear option will thereby be kept open. (They claim that the CEGB would be very unlikely to go through another Inquiry if their Sizewell B case is turned down). The enabling decision thus permits a PWR to be built; on Evans and Hope's calculations it is probable that it will prove a successful investment and a programme can follow. Should it prove unsuccessful, the programme follows only if economic parameters change in its favour. Their expected value of such a procedure is strongly positive as it subtracts a low probability (40%) loss on one station from a higher probability (60%) gain on a programme of stations. In addition, that expected value must also be compared with the loss of all possible benefits if the enabling decision is not made. This is clearly a powerful argument and it goes someway toward dealing with Collingridge's (1984 a and b) contention that the industry is caught between serial and piecemeal ordering. The enabling decision is piecemeal but permits the possibility of serial ordering given success, and hence will garner the benefits that that method offers. The delay in the introduction of the serial ordering then becomes the price the ESI (or society) pays for much greater certainty about the investment.

A similar development problem for the nuclear industry was thrown up by the CEGB decision prior to the Sizewell B Inquiry to extend the anticipated life for its large coal fired stations (76). This must delay the need for replacement capacity and requires an alternative economic justification for nuclear construction if the Evans and Hope conclusion is not followed. This justification is found in the concept of net effective cost (77). If a new nuclear station is built (despite no capacity need) it will displace other less efficient plant - this is pushed down the merit order. The fuel costs of the nuclear plant will (obviously) be positive but comparatively low since nuclear plant is fuel-cheap. If the expenditure which would have been made on fuel for the plant now dropped in the merit order (and burning less fuel) is subtracted from the nuclear fuel costs the 'net system saving' is derived. This will be negative because of the low cost nuclear fuel. If the system savings are more than sufficient to cover the capital and other charges on the new nuclear plant then that plant has a negative net effective cost and investment in it is justified on economic grounds despite the sufficient existing capacity (and/or, perhaps, no anticipated demand growth). The motivation for the investment is fuel cost saving; if the net effective cost is positive, then fuel saving alone is an inadequate basis to support the investment.

However, if the plant were built, not only does it push existing plant down the merit order, but also the plant now at the bottom of that order will be decommissioned (or 'mothballed'). Doing nothing leaves that plant operating (rarely) at peaks, so the cost of doing nothing is the cost of retaining that plant and that is termed the net avoidable cost. If the (positive) net effective cost is less than the net avoidable cost, then the investment in the new nuclear plant (not justified on fuel savings) is the correct choice. MacKerron (1982) notes that "by 1980 negative net effective cost had become the principal justification for nuclear investment plans" (78).

Clearly the above outline of the NEC/NAC analysis is a very broad picture and the detail of the costs to be included (interest during construction, decommissioning) the probable load factor and total output (derived from CEGB system simulations) is immense. However, its major problem is not the detail but, once again, the uncertainty that must surround the estimates. Keating (1985) gives methods for improving econometric forecasts, but writes: "... the effect of introducing all the improvements, even if fully successful would be to bring average absolute forecast errors down to the minimum achievable value: given the very considerable irreduceable uncertainty about the future, this would still be a high figure" (79). Since the NEC/NAC calculations depend on assumptions of future price movements and the CEGB system simulation, it is quite feasible to use Keating's proposal of using sensitivity analysis (scenario planning) as one way of taking account of uncertainty - this simply runs the simulations with alterations in the assumptions on the exogenous variables and re-estimates the forecasts. (The approach has been discussed, above).

VI.6.2 Risk Diversification

Franklin (1985) considers forecasting in the context of energy policy and argues that forecasts lead decisions to become increasingly subjective. Scenarios cannot guide unless a particular one is chosen, but that requires some means of attaching probabilities to each; but Franklin notes: "the forecasting and consequent planning of the last decade gives little confidence that this can be done for decisions that have their economic impact more than a few years ahead" (80).

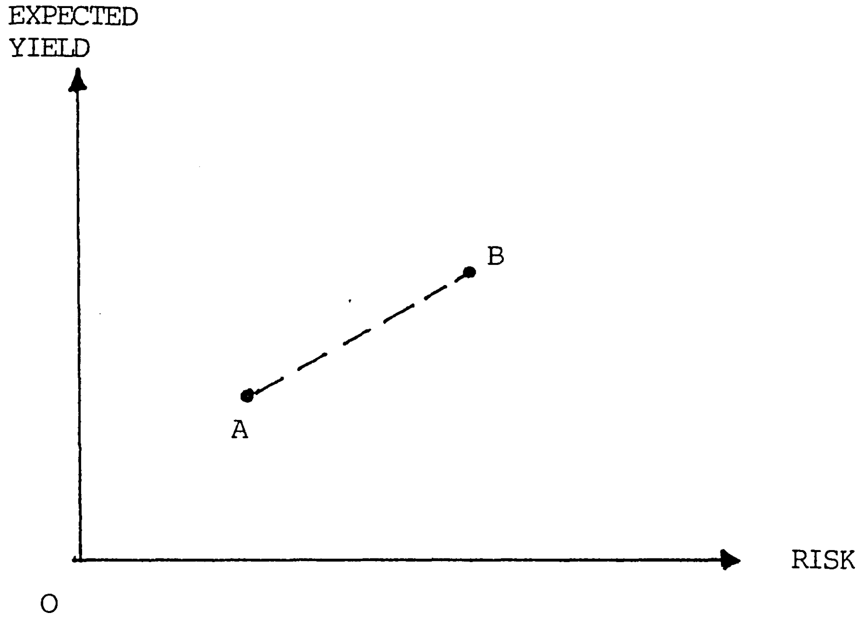
The policy solution Franklin offers is not to attempt to achieve the optimal cost-minimising plant mix of theory, but to go for a minimum regret policy, a "choice that will not turn out too badly under any foreseeable set of trends, or shock events" (81).

This policy is to develop coal, nuclear power and conservation (COCONUC) (82), which will lead to a sufficient diversity without becoming too expensive in creating a wide range of alternative systems. The strategy of fuel diversity is also one which the ESI has regularly promoted (83) and which is recommended in Flowers (1976) (84). The economic justification for such a policy lies in the theory of reducing risk through diversification.

The argument is that if the outcome of individual investment projects cannot be predicted with confidence, diversification can lead to the achievement of the desired output with a reduction in risk.

Figure VI.10

Risk/Expected Yield of Different Projects

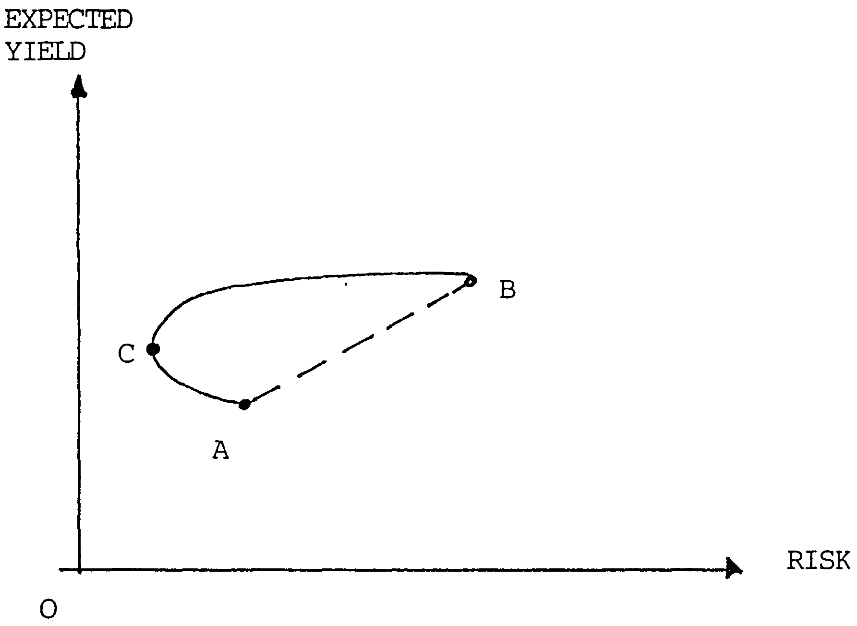


In figure VI.10 projects A and B have different risk/expected yield combinations. Assume the projects' outcomes are perfectly correlated (influenced by identical factors). If so, the performance of projects involving combinations of A and B lie along the line AB. [Thus if A is 'only coal' and B 'only nuclear', and if A and B are affected by the same events, then the risk/expected yield outcome for any coal-nuclear mix lies on AB].

Assume that the outcomes are such that if events lead one to do well, the other does badly, (figure VI.11)

Figure VI.11

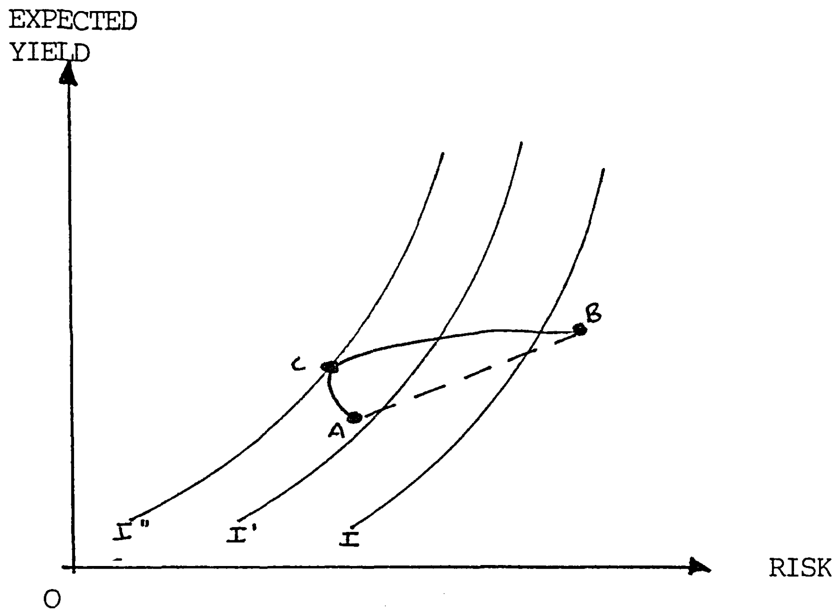
Projects with Negatively Correlated Outcomes



The decision to combine A and B now involves less risk than either just A or just B; the outcomes of such combinations lie along a line such ACB - the same yield but less risk because extreme outcomes are excluded. The greater the degree of negative correlation the greater the risk reduction opportunity offered by diversification. A risk averse investor (the policy proposed by Franklin (1985), Ramsey (1979), Evans and Hope (1984), Flowers (1976) and so on) will have indifference curves between risk and expected yield as shown in figure VI.12 (since yield is a 'good' and risk a 'bad').

Figure VI.12

Risk Aversion and Diversification



A risk averse investor can thus be seen always to prefer a diversified set of investments. Thus, despite the current oil prices and recent history, in July 1985 the Electricity Council wrote: "Although oil fired plant is expensive to operate, the large modern units are being retained to meet a probable longer term capacity need and to maintain primary fuel diversity" (85).

VI.7 SUMMARY

Clearly it is possible to undertake a SCBA for a new nuclear power plant (or programme). The standard cost benefit framework is easily suited to such an attempt: the programme will consume much steel, cement, land, specialised labour skills, scenic beauty; there will be a possible risk to health; the decommissioning task; some irreversible consumption and damage; and all of this over a substantial period of time. Allowance must be made for interest during construction, for fuel burnt elsewhere if the project is delayed, for pollution abatement measures and for qualitative problems (civil liberties, nuclear proliferation, the encroachment of hard technology, the centralisation of power and decision making). The straightforward maximisation problem is known (86) and the technicalities of ensuring commensurability of the data have been clearly presented (87).

Technological development and economies of scale give a bias in favour of big projects, all of which implies an "opportunity for multi-disciplinary teams providing a broad analysis" (88) - not only is the SCBA possible it is highly desirable, for otherwise avowedly risk averse strategies such as those of Franklin (1985) and Ramsey (1979) (89) cannot actually be said to be such. Only after a full economic appraisal can any view of risk be formed - and since, of necessity, energy policy decisions must involve periods of time so long that uncertainty assumes a major significance, the final decision is inevitably political. For the MMC to state that "(the CEGB's) case for nuclear investment is overwhelmingly an economic case" (90) is indicative that part of the SCBA can be, and is being, done, in the right place - the responsible industrial group. What remains is for the full range of relevant issues to be submitted to the analysis. Flowers (1976) does this in part, and makes the role of the qualitative factors clear. The economic analysis of Chapters IV and VI show the form the SCBA should take.

That this should be undertaken by a disinterested group is evidently central, since the economic contribution to a final decision must be independent of any political wishes. Mishan (1982b) discusses recent trends in cost benefit analysis and criticises in particular the proposals to devise and make use of sets of "politico-" or "ethico-" weights. This is the approach (which Mishan terms "revisionist") which argues that conventionally calculated costs and benefits might have their values changed by using weights determined either somewhere in the political system, or by an ethical consensus enshrined somehow in the constitution. Politico-weights might be used to reflect current views on income distribution or regional policy or the relative desirability of one type of power production system. But doing so takes all economic value from the SCBA - politico-weights will change as often as the political wind and any consistency is lost. The traditional method is strongly advised by Mishan as the only means by which the economist can usefully contribute to social decisions (see, also, Littlechild (1978)). The SCBA presents an independent statement of the impact of a programme and, thus "economic calculation (is) no more than a contribution to a political decision, one in which other social factors ... are also brought to the fore" (91). Since the final decision must be a political one, it should have the benefit of the advice available in the form of a full and independent social cost benefit analysis.

APPENDIX VI.1

	Average Load Factor %	Electricity Supplied (CEGB) TWh	Max. Demand Net MW	Max. Potential Demand MW	End Year Max. Output Capacity MW	5 Yr. Ahead Forecast		
							Capacity MW	Demand TWh
1956/7	47.9	79.525	17,668	17,668	20,644			
1957/8	48.0	81.3	19,311	19,311	22,240			
1958/9								
1959/60								
1960/1	48.5	104.74	24,445	24,445	27,067			
1961/2	47.9	114.8	27,020	27,856	28,959	66/7	38,000	
1962/3	49.7	127.7	29,520	32,100	31,687	67/8	43,000	
1963/4	50.6	132.1	29,937	30,488	33,157	68/9	56,173	
1964/5	51.8	141.0	31,328	31,779	34,359	69/70	59,000	
1965/6	51.4	148.8	33,358	36,077	36,905	70/1	54,000	238.0
1966/7	52.0	152.8	33,973	34,530	38,468	71/2	55,000	246.7
1967/8	52.0	162.7	35,818	35,818	41,944	72/3	54,000	238.0
1968/9	52.7	173.4	37,738	37,738	44,673	73/4	54,000	240.0
1969/70	54.7	180.7	38,153	39,652	46,857	74/5	53,200	252.0
1970/1	55.8	186.2	38,619	41,110	49,281	75/6	54,000	268.0
1971/2	54.9	190.5	39,925	40,509	54,322	76/7	54,000	272.0
1972/3	58.3	204.5	40,639	40,639	56,427	77/8	55,000	
1973/4	39.9	201.8	39,674	41,978	58,026	78/9	56,500	
1974/5	40.7	210.9	40,973	40,973	58,523	*81/2	54,000	
1975/6	39.6	204.6	41,353	41,353	58,667	*82/3	52,000	265.0
1976/7	40.7	208.6	42,110	42,110	56,365	*83/4	51,500	263.0
1977/8	42.9	211.9	42,803	42,803	56,326	82/3	49,500	248.5
1978/9	45.1	222.1	44,102	44,102	56,129	83/4	50,100	244.0
1979/80	44.7	221.7	44,225	44,225	57,029	84/5	47,300	239.9
1980/1	42.5	211.6	42,600	43,600	56,705	85/6	47,300	232.0
1981/2	42.9	210.3	42,597	42,600	55,185	86/7	44,200	220.5
1982/3	43.1	206.7	42,067	42,700	54,751	87/8	44,700	227.0
1983/4	45.5	212.7	42,243	43,500	51,028	88/9	45,000	229.5
1984/5	46.1	213.7	46,219	44,100	51,127	89/90	45,700	234.5

CEGB : CAPACITY; OUTPUT; MAXIMUM ACTUAL AND POTENTIAL DEMAND; AND FORECAST VALUES

Source (CEA); CEGB Annual Report and Accounts 1956/7 to 1984/5

* Six year forecast

NOTES TO CHAPTER VI

(1) USAEC (1974) p.24

(2) This narrow framework for a SCBA is noted by Owens (1981) in the context of planning inquiries. He also points out "throughout the 1970s the right of objectors to question need at motorway inquiries has been a contentious issue" (p.206).

(3) The view taken by Abbate (1979) is that people should be informed about efficiency of energy and about alternative sources, and prevented (presumably by taxation) from using inefficient means; but governments or institutions may not pass moral judgements on whether peoples' choices of energy-consuming products are good or bad.

(4) Schurr (1984) is pointing to restrictions imposed by OPEC; absolute restrictions such as that of natural gas in USA and the decline of North Sea output in UK; and the restrictions generated by increased environmental concern.

(5) Flowers (1976) p.71 para.155

(6) Starr (1982) p.251

(7) ATOM 309 July 1982 p.159, reviewing and quoting the OECD Steering Committee for Nuclear energy, May 1982.

(8) Maxey (1979) p.44

(9) Digest of UK Energy Statistics HMSO published annually

(10) Hull (1981) also points out that in periods of very slow growth the denominator (and perhaps the numerator) of the energy coefficient is very small, and the value estimated could be no more than the ratio of the errors in measuring each variable, and consequently meaningless. Negative values of the energy coefficient (implying economic growth will reduce energy consumption) also result in this period.

(11) Schurr (1984) pp.365-366; Meinel and Meinel (1979) p.11

(12) Meinel and Meinel (1979) p.6

(13) Department of Energy (1977) para.20

(14) Sweet (1983a) Chapter 4

(15) Some authors use GNP others GDP; since the precision of the calculation is not of paramount importance here, the variables are used interchangeably.

(16) Day (1980) p.9

(17) Sources of data for figures VI.1,2,3 and 6: Digest of UK Energy Statistics 1973 table 100; 1977 table 82; 1980 table 89; 1985 table 68.

(18) Electricity Council (1985) pp.45-46 (Electricity Marketing)

(19) Sources of data for figure VI.4 and 5: Digest of UK Energy Statistics 1971 table 9; 1974 table 10; 1980 table 10; 1985 table 9.

(20) Lonnroth and Walker (1979) p.22

(21) Thus from Electricity Council (1985): "In the domestic sector continued emphasis will be given to retention of existing space and water heating load by increasing awareness of the competitive position of the Economy 7 night rate against domestic gas prices ... In the commercial sector emphasis will be given to energy management aimed at improving the use of energy in buildings" p.45.

(22) Berrie (1983)

(23) Starr (1982) p.252

(24) Flowers (1976) para.479

(25) Collingridge (1984b) p.195

(26) Wigley and Vernon (1983) p.1

(27) Chateau and Lapillonne (1978) p.148

(28) Flowers (1976) para.466

(29) M. Samuelson in the Financial Times 28.1.86 quoting IEA 1984 Review: Energy Policies and Programmes of IEA countries.

(30) Collingridge (1984a) p.57

(31) All references in this section are to the relevant Annual Report.

(32) CEGB Annual Report 1978/9 p.13 para.152

(33) Day (1980) p.9

(34) Evans and Hope (1984) p.114

(35) Day (1980) p.10

(36) MacKerron (1984) p.301

(37) An intermediate approach is used by Hellman and Hellman (1983) in an analysis of major coal/nuclear power comparisons in the USA. They argue that using cost data supplied by the architect/engineer will underestimate actual costs substantially, given experience of these data. Second, regression analysis will be unreliable given the engineering and economic unpredictability of the nuclear industry. Their chosen solution is to begin with the cost data from the architect/engineer and to adjust it for unrealistic assumptions and errors. This approach allows them to re-estimate the studies they are investigating using data derived partly from quoted costs and partly from estimates based on a "desired and realistically achievable level of performance".

Provided the latter meets general approval the approach is not dissimilar to the scenario methodology, but is inferior since it evidently allows much discretion.

Komanoff (1980/81) also points to the unreliability of using capital cost estimates from engineering estimation as reactors are built in an environment of constant change - the costs cannot be known until the plant is completed.

(38) Rush, MacKerron and Surrey (1977) p.101

(39) Thomas (1982) p.36

(40) CEGB Annual Report and Accounts (1985) p.3

(41) Freeman (1983) p.14

(42) Rush et al (1977) p.102 Also, Williams (1980) has a detailed discussion of the background to all the nuclear power decisions up to the Windscale Inquiry.

(43) Hellman and Hellman (1983) p.XVI

(44) Ibid pp.4-6

(45) Because the accuracy (or probability distribution) of the new data is not known, forecasts cannot be given true confidence intervals; they become point estimates from a data set whose usefulness in guiding decisions can only be known if the decision is to go ahead.

(46) Collingridge (1974b) p.191

(47) eg. MMC (1981) para.5.126 "...the potential advantages arising from a steady ordering programme. In this context the CEGB has told us that recent French experience of a programme of PWR orders indicates that a unit cost saving of about 8% is achievable by the fifth order in the series".

(48) Freeman (1983) p.14

(49) See Williams (1980). The history of the UK experience is not the point centrally at issue here.

(50) ATOM 349 p.19

(51) Evans and Hope (1984) p.114

(52) Walske (1984) p.7

(53) Seneca and Taussig (1984) p.17

(54) Sors (1981) p.276

(55) Ibid p.282

(56) Ibid p.297

(57) Ibid p.299

(58) Ramsey (1979) p.16

(59) Highton and Webb (1981b) p.51. The SO_2 problem is also discussed by these authors in Highton and Webb (1980) and (1981a)

(60) Sors (1981) p.304
"SO_2 and sulphur compound releases from the UK and Western Europe fall as acid rain in Scandinavia"

(61) Ramsey (1979) p.1

(62) The proposition of biomoss generated electricity has cynically been termed the dark green scenario - green as it is benign, dark because it will not generate enough power to turn the lights on. This is an extreme criticism, but a proposal such as in Leach (1978) that increased conservation could render the nuclear debate redundant by reducing electricity demand to the point where the nuclear stations' output is not required, rests on (amongst other assumption) a co-ordination of conservation decisions amongst millions of consumers. Such decisions - trivial to the individual but significant when summed over society - are simply not likely to be made; moreover there is clearly the strong probability of the classic public goods problem of the free rider. Each individual will choose not to conserve energy on the grounds that his/her action is a negligible part of society's action; hence (s)he can get the benefits of society's conservation without the costs of conserving at home. Pearce and Jones (1980) also comment on this.

(63) Manners (1980) p.310

(64) CEGB Annual Report 1980 paras 104, 105

(65) Brett-Crowther (1980) p.293 also Rush et al (1977):
"Characteristic of so many major decisions on large technology projects in the 1960s the AGR decision was taken by closed and secret processes, which ... permitted no informed critical debate". p.104

(66) Lonnroth and Walker (1979) argue that energy decisions are politicised already as the government has to choose between the pace of nuclear development and advocating alternative policies.

(67) Wynne (1980) p.201

(68) Purdue et al (1984) p.279

(69) see Pearce and Jones (1980) p.274

(70) Purdue et al (1984) p.281

(71) Rippon (1984) argues: "... most of the arguments that have been presented at the Sizewell B Inquiry were thoroughly aired (in Europe) during the 1960s" p.261

(72) Wynne (1980) p.166

(73) Seneca and Taussig (1984) pp.10-17

(74) Fowler (1983) p.35

(75) The collapse of the Washington State nuclear programme represents a huge financial loss

(76) see Franklin (1984)

(77) see Select Committee on Energy (1980-81) Vol II p.555-575 CEGB Memorandum

(78) MacKerron (1982) p.29

(79) Keating (1985) p.134

(80) Franklin (1985) p.8

(81) Ibid p.8

(82) The "coconuc" policy is also to be found in Cmnd 7101 Energy Policy a Consultative Document

(83) see for example Electricity Council (1985)

(84) Flowers (1976) para.194

(85) Electricity Council (1985) p.27. The same diversification conclusion - but excluding nuclear power - is reached by Brett-Crowther (1980a)

(86) see Evans and Hope (1984)

(87) see Brandfon in Select Committee on Energy (1980-81)

(88) Bajay (1980) p.265

(89) And, in effect, all major commentators other than those who wish to end all nuclear development now.

(90) MMC (1981) para.5.120

(91) Mishan (1982b) p.42

CHAPTER VII

CONCLUSION

VI.1 INTRODUCTION

The central theme of this thesis is the value and role of economic advice in the formulation of energy policy concerned with nuclear power. That advice is made in the form of an economic calculation of benefits and opportunity costs arising from development of reactors and the nuclear fuel cycle. There are unique factors surrounding the nuclear case which lead to controversy and some extra difficulty in economic evaluation; some economists (1) have argued that such evaluation is not possible in this case, and the decision is an ethical or moral one. The contention of this thesis is that a social cost benefit analysis is possible, and represents an essential element in the final political decision, which would remain inadequately based without that advice. The econometric analysis and calculation of indirect costs and benefits does not provide a sufficient basis on which to decide the question of whether any nuclear development should go ahead. That is a broader, political issue to be decided politically, using the economic analysis as one element in the discussion. That analysis should be undertaken as an objective economic calculation in the form of social cost benefit analysis, since the latter technique has been developed to go some way toward dealing with precisely the type of problems that arise in the case of nuclear power.

VII.2 ENERGY POLICY

There are several characteristics of energy in general that make a coherent energy policy a necessary requirement for efficient resource allocation. In the specific case of electricity a major problem area is the influence of uncertainty. The long lead times involved in planning and constructing power stations (particularly nuclear reactors), and the resultant number of years for which demand and input price forecasts are required mean that the commitment of very large investment funds must be made on the basis of highly uncertain data. The project lead times will reduce as a learning curve develops (2) but the plant lifetime of 30 years is such that uncertainty will be a permanent feature of the forecasts. This can be mitigated to some extent by the use of scenarios which permit a range of possible futures to be considered rather than producing a single, best estimate.

Uncertainty is a reason why it is likely to be inadequate to rely solely on the market to determine energy policy. There is a view that it is impossible to improve on the free operation of the price mechanism in resource allocation decisions, since that mechanism makes use of all available information in a way that no government or corporate department could. Privatisation of electricity generation is perfectly feasible, in which case the policy decision on which type of power station to build would become a market decision. There is, however, a strong argument that market decisions are too short term in nature and that the degree of uncertainty surrounding nuclear power and the huge commitment of investment capital with no return for up to ten years, would shift the market against such a development, because of the time period involved. Consequently it would be unlikely that the requisite finance would be available.

A further reason for producing an energy policy would be as part of a deliberate attempt to improve the energy efficiency of the country and to allow strategic planning. In the UK this would relate to the prospective decline of North Sea oil availability, and to the desire to encourge diversity of energy supplies and the application of new technology. This is, in part, the classic argument against monoculture. In agriculture, if vast areas of land are devoted to one type of crop, then a disease specific to that type can devastate the harvest. Similarly if energy supply is heavily dependent on one fuel, that dependancy creates a substantial risk. Any adverse events relating to the fuel cause immense problems for energy supply (3). Thus, the French lack of indigenous energy resources and consequent dependence on imports is an important justification for the central decision to expand the electricity sector with major nuclear developments.

Finally, energy policy has a central role to play to the extent that economic growth is determined by energy supply. The suspect role of the energy coefficient, (the output elasticity of energy demand), in short term forecasting is discussed in Chapter VI, together with the arguments that in the longer term, the supply of energy at suitable prices may well be a highly significant factor permitting the invention, innovation and investment that produces economic growth. Once energy policy is deemed valuable on these grounds, the rate of market penetration of electricity, oil, gas and coal become elements to be established by that policy. However, the central problem will always remain that of uncertainty, and one approach to energy policy will be to devise investment programmes which aim to minimise the size of possible error rather than to achieve the theoretical economic optimum of cost minimisation. In electricity production such a policy would be 'coconuc' (coal, conservation and nuclear power), discussed in Chapter VI. With that approach as the underlying philosophy of the policy the SCBA can be undertaken to establish the economist's advice on future investment.

VII.3 ECONOMETRIC ANALYSIS

In Chapters II and III an econometric analysis of electricity production in England and Wales is presented. The advantages of the approach reported there lie in the properties of the model chosen for estimation; in particular its generality and the opportunities it offers for measuring the degree of substitutability or complementarity between inputs to the production process. The latter is a major area of concern in energy economics literature, and is clearly of direct relevance to policy making both at the level of the industry itself and the overall energy policy level. The translog production and cost functions are not self dual and different results will be obtained from estimates of each one. However the prices of inputs may be assumed essentially exogenous to the ESI hence the cost function is chosen for estimation.

Manipulation of the translog model allows a system of equations to be derived, each relating the share of expenditure devoted to a given factor to the prices of the inputs. The model is very general and imposes no constraints on the data. Instead nested hypotheses may be tested sequentially by imposing successive restrictions on the model. The restricted equations can be reestimated and the restrictions tested.

The results of estimating the factor share equations allow direct calculation of the own- and cross-price elasticities of demand for each factor and of the elasticities of substitution between pairs of factors. By assuming separability between inputs, the model allows this to be undertaken in a two-stage procedure. The first stage is to estimate a fuel subsystem and derive the elasticities for just the fuel inputs, coal, oil and nuclear fuel. The policy implications of these results lie in the evidence they give on how substitutable the different fuels are. Given a policy of fuel diversity for strategic and planning reasons, evidence that nuclear fuel is becoming increasingly substitutable for other fuels gives impetus to the policy.

The second stage is to estimate a system of cost share equations for the inputs labour, capital and fuel and compute the elasticities. The degree of input substitutabilty is an indication of how the industry might be best developed; for example capital/labour substitutability is an indication that increasing the capital/labour ratio (with bigger generating sets and less employees) is likely to be a successful policy.

The results reported here throw light on the debate over factor substitutability at the levels of fuel use and of the major inputs to the electricity production process. As such they have clear implications for policy with respect to the development of electricity, to the size of its market share, and to the expansion of the nuclear power sector. A particularly important result to emerge from this analysis is the change that occurs following the 1973/4 oil price shock. The elasticities derived in the overall system estimation all show a shift when comparing the periods 1963/4 to 1973/4 and 1974/5 to 1982/3. Pairs of inputs which are substitutes in the first period become more so in the second; pairs which were complements in the first period become substitutes in the second. While these results must be regarded as preliminary, given the short sample period, they, nevertheless, provide important policy information, since they do indicate how the industry has been able to react to the shock, given the underlying nature of the production process brought out in these estimates.

Energy policy makers need information on energy demand and supply; within that on electricity demand; and within that on how to meet that demand with different fuel mixes and changing capital/labour/fuel ratios. The results quoted here give information on the last of these points directly, and indirectly on the second point. Using them for forecasting is possible, but drawbacks with the data do indicate a limitation there. This outcome is achieved using economic theory and econometric application; it offers a direct input to the policy making process and is clearly a relevant contribution from economics.

VII.4 POLICY AND SOCIAL COST BENEFIT ANALYSIS

Nuclear power is a contentious issue (4) and should, therefore, be subject to the political process of decision making (5). Part of that process must involve debate over purely political issues. These would include such things as the desirability of economic growth and the expansion of the electricity sector. Within the latter is the argument of how that sector should grow; should it involve construction of bigger generating sets which might imply an increased centralisation of decision making and the creation of a technocratic elite, whose knowledge is so esoteric that lay people are excluded from comprehension, and thus from effectively contributing to decisions?

The growing bureaucracy and centralised control produced by big (or 'hard') technology would prohibit local intervention and coerce people into tolerating risks which they might prefer not to face. In this view nuclear technology appears "harder" than any other and the "explicit political process" is justified. If so the merits of growth, the need to expand energy supply to permit that growth, the experience of nuclear power and the social limitations of small localised energy technology can be expounded. There will be economic contributions to the debate but these areas, together with weapons proliferation, are essentially political.

Similarly there will be areas which are technical, but, nevertheless, have economic considerations. Safety standards must be set and controlled by some central organisation such as the NII or HSE. However the chosen standards determine capital cost to some extent and retrofitting of existing stations can alter the framework of the investment appraisal of future plants. Moreover, risk analysis will, in part, determine the conclusions on safety standards, but it is clear that public perception of risk is very different from the actuarial-type calculations made by the industry. Either the public need more information so that their perceptions may be adjusted, or their subjective view must be given more weight, which will involve increased capital spending on nuclear stations, on waste disposal (and the whole fuel cycle). The latter would be the case if it were agreed that tiny probability/large consequence events are better measured by public fear than by apparently more objective probability assessment. The problem is compounded by the fact that operating data are slow to accumulate in the nuclear industry, and some data exist only in probabilistic form since the accidents or events they attempt to measure have never occurred.

What remains is a problem of economic evaluation that fits the SCBA framework ideally. Forecasting of energy supply and demand; of electricity's role within that; and of the relative expansion of nuclear power, have already been discussed within the context of an econometric analysis of the energy sector. Sensitivity analysis can be undertaken by changing assumptions (or estimates) or by assigning asymmetric probabilities to such values. Scenarios may be developed, within which the forecasts may be made, allowing a broad view of possible future trends.

The policy maker needs to estimate the overall direct and indirect costs of any project and the SCBA framework permits this. The direct costs are published by the CEGB from past experience and future costs are a matter of assumption. The scenario approach can accommodate the question of possible extreme capital cost inflation (referred to by Komanoff (1981) and Hellman and Hellman (1983)) and the opportunity for a learning curve to develop from construction of a family of reactors based on a single design.

Valuation of intangible costs and benefits is an integral part of the SCBA. Failure to include these means that the analysis is incomplete and conclusions drawn from it inaccurate. The damage function is, as has been discussed, a phenomenon which is as yet poorly understood and attaching prices and costs to events may well not be possible. However, knowledge is growing and models of exposure assessment are being developed to avoid the otherwise impossibly complex monitoring needs (see Sors (1981)). Failure to undertake this evaluation will bias the decision; in that event future choices may be prejudiced by a wrong choice made now.

This leads to another area of importance - the application of the theory of option value to nuclear power (see Chapter IV). The SCBA framework forces the economist to ask the relevant questions about environmental impact, cost implications of safety and risk analysis and so on. Some cannot yet be answered except by varying the assumptions accommodated within scenarios. Yet making the questions explicit makes the significance of the decision clear. A decision to abandon nuclear power projects now would shut down parts of construction industry, the design teams, research throughout the fuel cycle and, effectively, prohibit future development, except through imports. An option in the future is thus lost. Developing nuclear power creates waste, power stations which will need to be decommissioned, and an irreversible change to the environment - by definition some option is lost in the future. Thus what appear to be purely moral or ethical questions can be operationalised in a SCBA - not necessarily with monetary values, but certainly in a way which implies the direction in which costs should be adjusted.

The alternative approach of a Planning Inquiry attempts to cover economic, technical and political areas and to achieve a definitive, legalistic conclusion. Yet such a conclusion does not exist. Political views cannot be "factualised", and the vast scale of the Sizewell B Inquiry (340 days) mean that the public has probably learnt little (6). Wynne (1980) sees the Planning Inquiry as a ritual designed to reassure the public, since in the case of nuclear technology definitive decisions cannot be made. The timescale and the financial commitments are so great that changing circumstances may be inadequate to change the direction of a project once under way.

However, a SCBA used as an objective economic contribution to a wider political decision has certain distinct merits. It can use econometric analysis such as that presented here to provide evidence on the degree of substitutability between various fuels and between other inputs and fuel, and hence, indicate how the industry may develop. It can make explicit the environmental impacts that are relevant, the level of knowledge of them and how that may be quantified. It can explore the options lost or made available by different decisions on nuclear expansion, and detail the problems of equity between present and future generations that arise from decisions made now having long term, perhaps irreversible, effects on both the environment and living standards. By using willingness to pay, and compensation required as the measures of benefits and costs, the SCBA reflects society itself and not some political view of what should be; consequently it provides an invaluable piece of objective evidence.

NOTES TO CHAPTER VII

(1) See Pearce (1979), Kneese (1972)

(2) as has been shown in the Torness and Heysham II AGRs, being built to both time and budget

(3) Hence, the CEGB preference for fuel diversity, analysed in Chapter VI

(4) Hence Pearce et al (1979) demand that it should be on the "national agenda"

(5) Flowers (1976) argued for independent assessment of nuclear power, "to enable decisions on major questions of nuclear development to take place by explicit political process" (para 524)

(6) See Greenhalgh (1984) and Purdue et al (1984)

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