APPENDIX A

Pilot Study 1

A Comparison of the Economics of Nuclear, Coal, and Gas Power Plant Using Sensitivity Analysis and Risk Analysis

A.1 Introduction

This pilot study is aimed at 1) establishing the feasibility of model replication, 2) examining the methodological issues involved in a case study based modelling experiment, 3) determining the limitations of sensitivity analysis and risk analysis in modelling uncertainty, 4) exploring the implications for model completeness, and 5) providing the rationale for model synthesis. The level of detail documented here is reflective of subsequent modelling exercises.

At time of writing in July 1992, the nuclear review in the UK ESI promised for 1994 provided a rich background and rationale for the comparison of plant economics. Nuclear power has always been a highly controversial topic, with disagreements surrounding its real costs, technical complexities, huge uncertainties, and the evaluation of intangibles. It is a real event that is bound to provoke debate up to the actual date of review, thus providing plenty of evidence and results for our comparison. The following script (courtesy of Kiriakos Vlahos) gives a brief background of the inquiry.

> While the Hinkley Point C inquiry was under way, the UK government took the decision to postpone any decisions about the nuclear development programme until a review of nuclear in 1994. It also withdrew the nuclear industry from the privatisation programme and formed a new company, called "Nuclear Electric" which would operate existing nuclear stations.

> The Hinkley Point C inquiry approved the development of the new power station on the grounds of the "Non-Fossil Fuel Obligation", although the economics of nuclear at the time looked desperate compared to either coal or gas.
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> Since then, concern about the environment and especially the greenhouse effect has been growing, and the EEC is planning to introduce a carbon tax on fossil fuels. Such a tax would improve the economics of nuclear power stations, since they do not produce the main greenhouse gas CO_2, neither do they produce SO_2 and NO_x in the generation of power.
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> In addition, Nuclear Electric has been performing quite well in financial terms, producing substantial profits, of course to a large extent due to the "nuclear levy." But they did manage to improve the availability of the AGR stations and to increase the market share of nuclear overall. Nuclear Electric and BNFL, the two main companies of the UK nuclear industry, are keen to build new nuclear power stations and they even called for the review date to be brought forward. This has been declined by the government.
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> Developments in the electricity and gas markets are also relevant. A large power station building programme coincided with privatisation, and Combined Cycle Gas Turbine (CCGT) is the type of plant that will inevitably dominate the new power station market. If projections materialise, gas consumption will double in the UK by the year 2000. Whether the gas industry can produce that much gas at competitive prices is an open question. The UK and European gas supply and demand situations need to be carefully examined.
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> The latest news is that Nuclear Electric wants to build "Sizewell C" a successor to "Sizewell B", but with double the size (about 2.5 GW). They estimate that this follow up will achieve significant economies of scale and will be economic compared to competing electricity generation technologies.

The government's decision in 1994 depends, amongst others, on the ability of nuclear power to compete against other plant especially in anticipation of the likely over capacity due to gas-fired plants, which are expected to dominate the early part of next century. This pilot study examines the economics of nuclear power and its immediate competitors, coal and gas, the most influential factors affecting the final cost of electricity, the impacts of the proposed EC carbon tax, and the overall effect of uncertainties.

Marginal or levelised cost analysis is used for assessing plant economics rather than constrained optimisation of the entire system. The main data used in this study originates from UNIPEDE (1988) and OECD/NEA (1989) reports, which are referred as UNIPEDE and OECD throughout the study. Electricity costs are analysed in a global context to give a broad perspective on realistic ranges. Major components of cost are then presented and discussed. Uncertainties are assessed by the techniques of sensitivity analysis and risk analysis. Extensions to this study are suggested at the end.

A.2 Modelling Approach

The ***levelised cost of electricity***, also known as the average or uniform discounted cost, is the accepted method for comparing the economics of different power plants. This method is extensively detailed in IAEA (1984), UNIPEDE, and OECD. All the costs are discounted to the present value at a certain point in time so that the terms, which are expressed in constant money of that given date, can be summed and divided by the discounted electrical output. For a project in the United Kingdom, this value represents the cost of electricity generation in pence/kWh.

This study identifies the main components of the cost of electricity and the major factors that influence them. It explores the extent to which these components contribute to the final levelised cost under the impacts of varying discount rates and other factors.

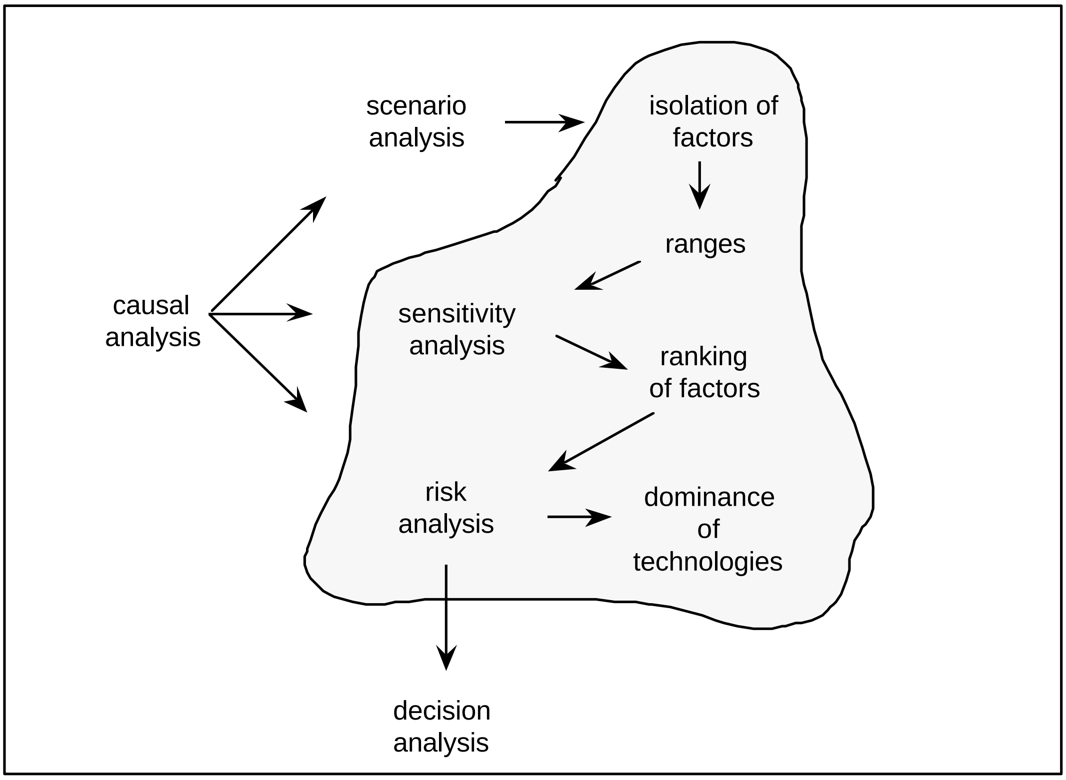
Instead of giving a point estimate for the cost of electricity, this study uses sensitivity and risk analyses to give a realistic range of estimates. A realistic range contains the most likely values, and in this case, is qualified within the international context, specifically of plants to be commissioned in the last five years of this century in industrialised countries. This deterministic analysis reveals the impacts of the major factors upon baseload coal-fired and nuclear power stations in the United Kingdom. The same approach can be extended to other types of plant.

First, the factors that influence power plant economics are isolated by taking international comparisons, thus giving a broader perspective on uncertainty and possible interactions between these factors. Ranges for the main parameters are extracted from the recent OECD and UNIPEDE reports by conversion to a common currency and then taking the minimum and maximum values for all OECD countries surveyed. The range for a given parameter is then reduced by discarding those outer values that reflect unrealistic circumstances in the UK sense, e.g. extremely high fuel prices or subsidies specific to a particular country. These ranges are then used as bounds in the sensitivity analysis. Data for UK coal and nuclear power plants are taken from both studies and used as base cases in this paper. Many countries are represented in both studies, thus allowing for data comparison and validation. Where input data is not available, the parameters are calculated from the respective contributions in levelised costs.

The approach of following sensitivity analysis with risk analysis has been advocated in standard texts on investment appraisal under uncertainty, e.g. Hull (1980) and Clemen (1991). Indeed, sensitivity analysis has been widely acclaimed, e.g. by Rappaport (1967) and Hertz and Thomas (1984), as a logical adjunct to deterministic capital budgeting, if not a necessary first step in understanding the nature and impact of risk.

The important factors that influence generation cost are first identified. The ranges of values are extracted from published sources for sensitivity analysis and risk analysis. The basic factors are defined in terms of the likely ranges of values and their impacts, the nature of relationships (linear or non-linear), and the magnitude of impacts. Progressively the assumptions are dropped and constraints tightened, until a sufficiently realistic model of uncertainty is represented. The steps are illustrated in the shaded region below.

Figure A.1 Uncertainty Modelling



A.3 The Cost of Electricity Generation

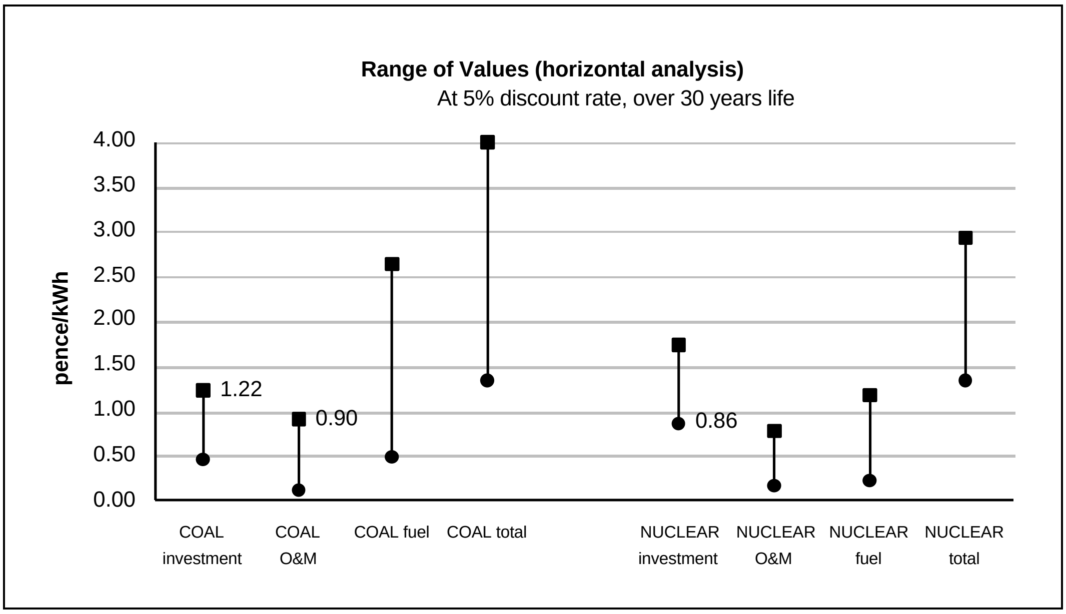
A.3.1 Range of Levelised Costs

The levelised costs of plants to be commissioned in the near term are the costs to the generators not the price charged to consumers. This study examines the levelised costs of plants to be commissioned between the years 1995 and 2000 for all the OECD countries surveyed in OECD and UNIPEDE reports.

The levelised cost of electricity generation by coal-fired plants given in the OECD and UNIPEDE reports ranges from 1.33 to 3.99 pence/kWh. These costs were calculated from the raw data supplied by OECD countries discounted at 5% for 30 years to constant currency of January 1987. The levelised cost consists of three components, namely, contributions from the initial investment, annual O&M, and the variable fuel cost. The variability in contribution by fuel is the greatest for coal, 0.47 to 2.64 pence/kWh, over twice as much as investment, which ranges from 0.47 to 1.22 pence.

Calculations for nuclear power stations to be commissioned in the same period reveal a narrower range of costs, 1.33 to 2.94 pence/kWh, with the reverse order for coal in relative contributions of investment and fuel. This is not surprising as investment costs are much higher for nuclear than for coal plants. Fuel costs show great variability because the expectations of future fuel prices differ widely amongst these countries. Figure A.2 illustrates the range of values for all the countries studied.

Figure A.2 Horizontal Analysis of Value Ranges



This kind of horizontal analysis shows the range of costs across the countries surveyed. Although cost differences are due to different conditions in each country, the general order and magnitude of difference can be used to assess sensitivities of cost in a particular country.

A.3.2 Variability in Cost Components

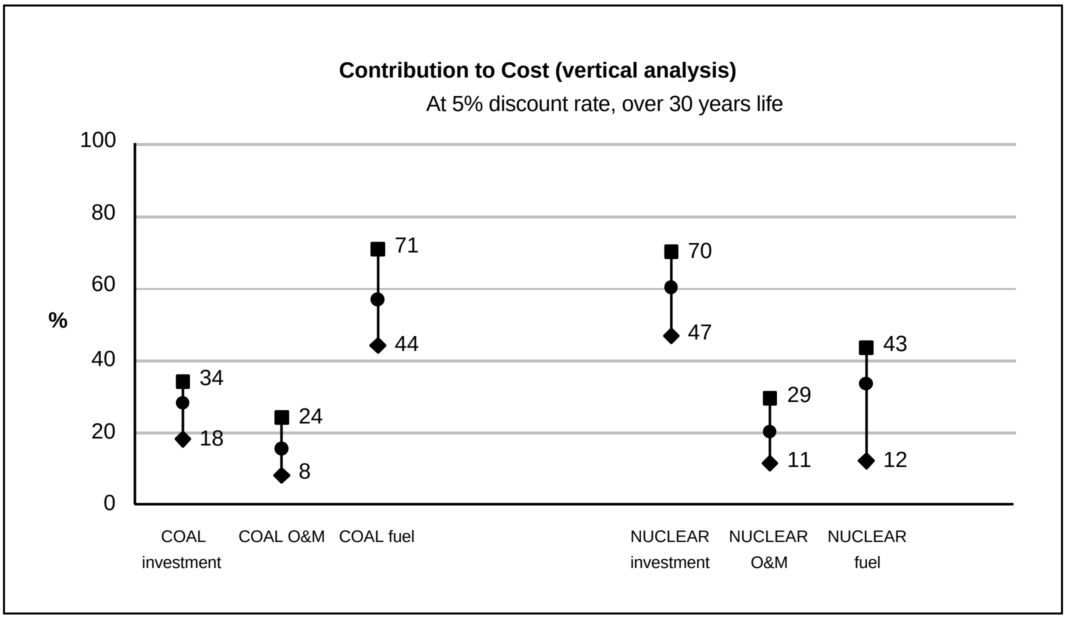
Variability across countries can be examined by comparing the ratio of the largest to the smallest cost by component, e.g. the maximum divided by the minimum for cost due to investment (or O&M or fuel) across all countries. Here, the greatest difference is the contribution by the O&M cost of coal-fired plants, the largest being 8.31 times the smallest. But the range is small: 0.11 to 0.90 pence/kWh in absolute terms compared with other costs. Even the smallest discrepancy claims a factor of two, i.e. the largest nuclear investment cost is twice the smallest. For both coal and nuclear fuel cost contributions, the largest is 5.55 times the smallest.

Although differences between countries are not the subject of this study, it is nevertheless interesting to note such a range of difference in similar technologies among industrialised nations.

A.3.3 Contribution to Cost

While comparing costs across various countries raises the uncertainties of exchange rates and different assumptions made by each country, a vertical analysis, as shown in figure A.3, eliminates these issues by looking at each cost component in relation to the total. Again the minimum and the maximum are taken of the proportions for all OECD countries surveyed to set the maximum bounds used in the sensitivity analysis that follows.

Figure A.3 Vertical Analysis of Cost Contribution



Compared to other components, O&M contributes least to the total cost for both coal and nuclear. Investment contributes between 18 and 34% to the cost of coal, while it is much greater for nuclear, being 47 to 70%. The relationship between investment and fuel is again reversed for nuclear and coal, i.e. the contribution by investment is much higher than that by fuel for nuclear (and the opposite for coal).

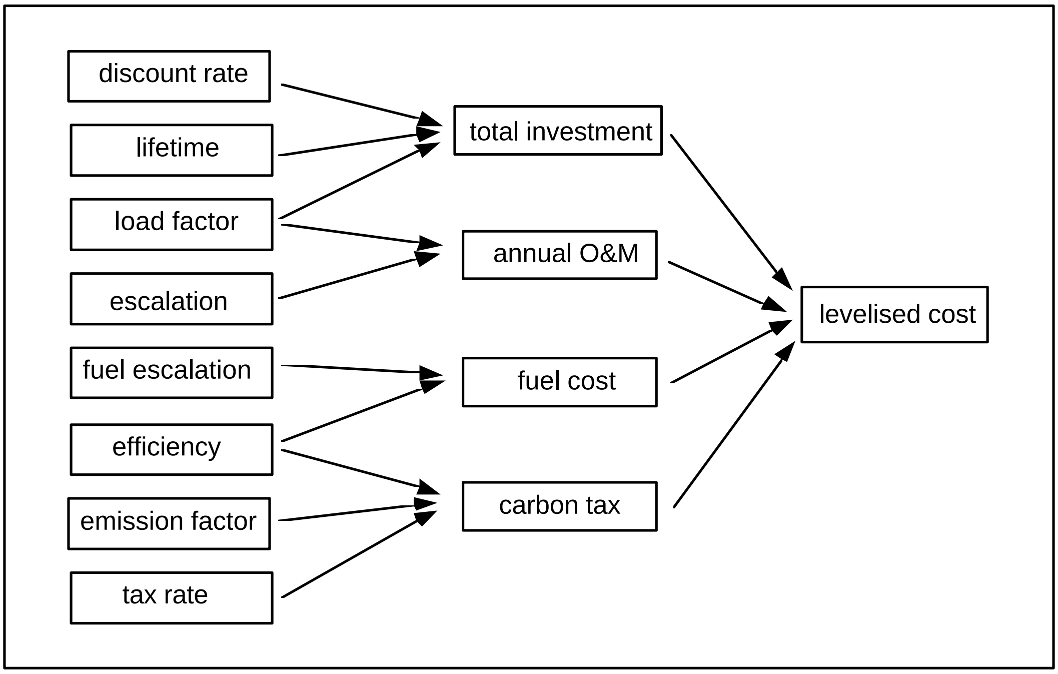
Such range diagrams depict the relative importance of different components within a single technology and the same component between different technologies. The length represents variability, the longer it is the greater is the range of possible values. Nuclear fuel has the greatest variability, contributing anywhere from 12 to 43% of total cost. The height represents the importance of the component, the higher it is the greater the contribution. The major components of coal and nuclear are due to fuel and investment costs, respectively, each of which contributes up to 70% of final cost of electricity generation.

A.4 Major Components of Cost

The UNIPEDE and OECD studies were conducted in 1988 and 1989 respectively, before discussions of a carbon tax came into full swing. Grubb (1989) and others have discussed the effect of a carbon tax on the relative competitiveness of fossil fuels for electricity generation and its effectiveness in curbing global warming. Using raw data and established conversion rates from these reports, a carbon tax can be calculated to see its effect on the final cost. The carbon tax component is included in this study to represent increasing environmental concerns through externalities.

Aside from the costs of investment, O&M, fuel, and carbon tax, the drivers of the four cost components are discount rate, life, load factor, escalation rates, efficiency, and carbon dioxide emission factor. These factors are depicted in figure A.4, with arrows representing "influences."

Figure A.4 Factors Influencing Cost



Each of these factors are defined next. The ranges of input values are taken from the two reports and adjusted with assumptions and approximations. The costs are expressed in constant US$ and ECU of January 1987 in OECD and UNIPEDE reports respectively. These cost figures are converted into sterling using the equivalent exchange rates at that time.

A.4.1 Assumptions

The UNIPEDE and OECD reports could not have based their calculations on fixed uniform scenarios, for the figures were simply collected from the participants without adherence to a priori rules. Instead their aim was solely to calculate levelised costs using the input figures provided. The input figures, such as capital costs, fuel costs, and load factors, vary from country to country, and the differences are explained in the two reports. Each country has its own assumptions about fuel prices and trends, especially for the stages of the nuclear fuel cycle. Most countries expected future coal prices to soften such that nuclear generation costs would not be that much cheaper than coal generated electricity. OECD goes further to seek an independent view from the Coal Industry Advisory Board, whose average of best estimates was significantly lower than majority of the countries although higher than some respondents.

Generally speaking, differences in capital costs are associated with costs of actual construction, commercial bids, design studies, regulatory requirements, and updating of older data. Cost of labour and welfare charges factor into the running costs and, along with other figures, are tempered by the economic situations in each country. As all costs are converted into a common currency, some conversions may be distorted due to the over or undervaluation of the national currency to ECU or US$ in January 1987 when the exchange rates were taken.

Capital investment of new coal-fired plants is largely burdened by the additional cleaning equipment, which depends on the type of sulphur and nitrogen oxide removal processes. Other capital cost differences are due to the economies of scale in unit sizes (315 to 840 MW for the UNIPEDE study, 165 to 850 MW for OECD study.) Similarly, the number of units on the same site contributes to the scale effects in investment and running costs. In other words, marginal costs decrease with each incremental MW or unit on the same site.

With reference to long term uncertainties, UNIPEDE considered the risk of error in determining total generating costs. This risk lies with the price of natural uranium and the cost of irradiated fuel management for nuclear generation and in the long term price of coal for coal-fired generation. However, it did not investigate the magnitude or likelihood of the uncertainties nor the time scale of what is meant by “long term.”

A.4.2 Ranges of Values

Rather than inventing pseudo highs and lows for the different values needed to calculate costs or basing the study on historic costs, we use “realistic” ranges of similar plant types in OECD countries. These figures refer to plants that will be commissioned around the same period of time. They have already been deflated and discounted to a given date and converted to a common currency.

As mentioned previously, each country submitted its figures based on its own assumptions and expectations of the future. Taking the range of input figures runs the risk of ignoring conflicting assumptions about fuel prices, regulatory scene, environmental standards, and technological developments. For example, the low cost of fuel in one country may be due to its proximity to the source, whereas, the high cost of fuel in another could be due to its unlucky experience in procuring a different grade of fuel in the past. However, by taking the entire range in such a sensitivity analysis, we can be sure of encompassing all possible and some improbable.

Some cost differences are structural due to the regulatory framework, economic conditions, industry organisation, or existing infrastructure in a country. Existing and target plant mix, status of over or under capacity, government subsidies, environmental concerns, and various other factors contribute to new plant costs. These differences cannot be generalised for any ranges, but for the sake of completeness, the range over all countries ensures that all possible values are included.

Initially, ranges are taken from international studies for the sensitivity analysis. Later, these ranges are adjusted for the UK case and revised by more current views.

A.4.3 Investment

Most capital and related costs are incurred in the form of construction cost during the construction period that precedes commercial commissioning. During this period, interest during construction (IDC) is accumulated according to the investment schedule and prevailing interest rates. Both OECD and UNIPEDE studies computed the interest during construction using an interest rate equal to the discount rate. Therefore, when the discount rates were varied in the sensitivity analysis, IDC would change accordingly. It may be argued that the use of an interest rate in the calculation of the IDC relates to a financing decision whereas the use of a discount rate in the calculation of levelised cost follows an investment decision. By this token, the interest rate and discount rate are not necessarily be the same, especially since the interest rate used to calculate the IDC can vary with time and the kind of financial arrangement. In contrast, a fixed discount rate is used to revalue all other costs to a specific date. This aspect of capital cost requires detailed modelling and in-depth investigation beyond the scope of this pilot study. For simplicity, the IDC is taken as a lump sum and included in the investment cost in the sensitivity analysis. Thus changing the discount rate would not affect the IDC, and the financing and investment evaluations are kept separate. We also include the IDC in the risk analysis that follows, as the IDC relates to the time value of money.

In anticipation of stricter environmental legislation in the future, the costs of desulphurisation and denitrification equipment are included in the initial investment for coal plants. It is assumed that the reduced plant efficiencies due to this additional equipment have already been taken into consideration.

Considerable scientific uncertainty surrounds the last stages of nuclear plant operation, namely, dismantling and decommissioning. Actual decommissioning costs could exceed provisions. Therefore it is important to consider this in the capital costs. For comparison purposes, this is included in the investment costs for both coal and nuclear. The provision for nuclear is much greater than that for coal and the magnitude is more uncertain. This provision depends on whether the dismantling is partial or total and the time elapsed between the final shutdown of the station and the start of decommissioning. The impact of this provision is not considered in detail here.

The investment cost for coal ranges from £475 to 1,211 per kW of installed capacity. For nuclear, it is £868 to 1,725 per kW of installed capacity.

A.4.4 Operations and Maintenance

In general, fuel costs make up 80% of the running costs, with the remaining 20% due to operations, maintenance, and labour . Although there are fixed and variable portions to the O&M cost, it is approximated as a single fixed annual cost in this study. O&M cost component is the smallest of the three major components after fuel and investment as shown in the previous section on costs. Specific cost of labour and welfare charges depend on the economic situation in each country.

The OECD report gives total O&M costs. This figure is taken as an annual fixed O&M cost with zero variable O&M cost. The bulk of this cost is due to the portion of labour in fixed costs and the amount of labour employed at site.

Because the UNIPEDE report does not list O&M costs, a slight approximation must be made to derive the O&M cost as an input. The annual fixed O&M cost is calculated from multiplying the average discounted O&M cost per kWh (in the reference case of 5% discount rate and 25 year life) by the annual utilisation of 6,600 hours. Again, the resulting annual fixed cost is assumed to include the variable component of O&M cost.

O&M costs for coal varies between £ 6.92 to £59.74 per kW per year, while the range is smaller for nuclear, being £16 to £49 per kW per year. To compensate for the variability in O&M costs, a modest range of escalation rates is applied in the sensitivity analysis.

A.4.5 Fuel

The treatment of nuclear fuel differs greatly from that of fossil fuels in generating electricity. The calculation of the final cost of electricity generation due to the complicated nuclear fuel cycle requires additional coefficients, which are not evident in the two reports. For this reason, the output values of pence/kWh attributed to fuel was used. A more detailed study could calculate the conversion from raw uranium concentrate, through the nuclear fuel cycle, to a more accurate cost of fuel contribution.

Fossil fuel prices are available by equivalent heat, weight or volume. For instance, oil is typically measured in barrels, coal in tonnes, and natural gas in cubic metres or therms. Measurement by heat content standardises for all fossil fuels. To relate these fuel prices to the plant heat rate, the price per equivalent heat is used, e.g. £ per GJ.

Coal prices vary considerably between countries depending on the location of the power plant (i.e. its proximity to sources of coal), whether it is imported or domestic, and the subsidies and taxes on fuel. The high prices of domestic coal in Germany and Spain are an order of three to four times the cost of imported coal elsewhere. Likewise, the cheap price of abundant domestic coal in Western Canada is half the cost of the cheapest imported coal in the world. In both reports, imported coal prices were given in the UK values. Given that the final analysis is aimed at sensitivity of costs in the UK, a logical conclusion is to tighten the range of possible coal prices by restricting the analysis to imported coal. These imported coal prices varied from 89 pence to £2.24 per GJ, which compares reasonably with international traded prices.

The price of steam coal in the UK (IEA, 1991) increased from £ 1.26 to 1.81 per GJ between 1980 and 1990, with an average high of £1.86 in 1988. After deflating, the price has fallen in real terms. Negotiations between the major generators and British Coal (Financial Times, March 1992) indicated an expected price of £1.50 to the current £1.63 per GJ range, while Scottish Power had been able to procure coal at £1.00 per GJ. Average prices of coal purchased by the major UK electricity generating companies (Department of Energy, April 1992) reached as high as £1.99 /GJ between 1986 and 1992. Thus the derived range of £0.89 to 2.24 per GJ is not unrealistic for evaluating the case of UK coal fired stations. The levelised costs reported in OECD and UNIPEDE are most sensitive to assumptions about future fuel prices. For this reason, comparisons with published sources are necessary to establish credibility.

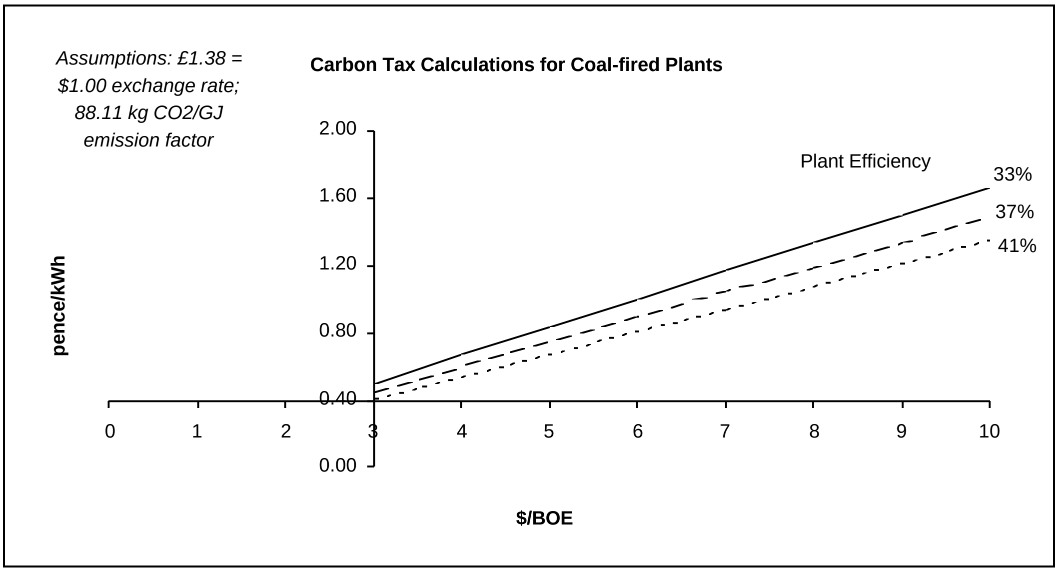
A.4.6 Carbon Tax

The parameters specific to fossil fuels necessary to calculate the carbon tax are absent from these two studies. Conversion rates such as carbon dioxide emission factors, heat content, and plant efficiency are readily found in recent policy and economic studies on the carbon tax. However, these policy-oriented papers do not specifically state many of their assumptions for the numbers. Tax units are expressed in \$/ton and \$/BOE. While BOE is understood to be the amount of fuel equivalent to the CO_2 released from burning a barrel of oil, it is unclear whether the unit of "ton" refers to the long ton, the short ton, or the metric tonne. Not only are the units misleading, there are at least two ways to calculate the tax effect: by carbon content and molecular weight or by carbon dioxide emission factor. To establish a common basis for the calculation of carbon tax, values for these parameters of oil, gas, and coal are taken from various papers and recalculated to tally against the original results. This type of multi-source analysis establishes the inter-relationships and produces a range of credible values. Realistic ranges of such parameters can be found by using figures from various sources. [See Ontario Hydro 1989, Hoeller and Wallin 1991, and Eyre 1990.]

The EC carbon tax is a specific tax levied on the equivalent amount of CO_2 released by burning a barrel of oil. A barrel of oil is approximately equivalent to 7.64 tonnes of oil. Given a heat content of 42.6 GJ/tonne and an emission factor of 75 kg CO_2/GJ, burning a barrel of oil emits approximately 418.19 kg CO_2. The fuel equivalent emission factor used in the calculation for other fuels is 7.64 / 42.6 / 75 = 0.00239 BOE/kg CO_2. Without specifying the exact grade of coal for the range of emission factors (71.7 to 108 kg CO_2/GJ) and plant efficiencies (25 to 45%) and \$/£ exchange rates (\$1.40 to \$2 = £1.00), the effect of a \$3 per BOE carbon tax would range from a low of 0.21 pence/kWh to a high of 0.80 pence/kWh. Based on the "relatively uniform generating technology of coal-fired stations" surveyed in the OECD and UNIPEDE reports, this study assumes that similar types of coal could be used in all stations. In other words, an average carbon dioxide emission factor of 88.11 kg CO_2/GJ could be used to calculate carbon taxes.

In 1992, the European Commission is proposing an incremental carbon tax of $3 in 1993, $4 in 1994, rising by $1 each year until $10 in the year 2000. In this study, the same amount of tax is applied to every single year for the entire economic life of the plant. Thus the no tax scenario can be compared to the high tax scenario of $10/BOE. The actual impact of an incremental carbon tax would lie in between the two. Figure A.5 illustrates the impact of a carbon tax relative to plant efficiency.

Figure A.5 Carbon Tax Calculations for Coal-fired Plants



As seen from above, the contribution of carbon tax is fairly insignificant at the $3 level. But at the $10/BOE level and assuming a low plant heat rate, it could double the cost of cheap coal-generated electricity.

A.4.7 Efficiency

The amount of carbon dioxide released when a fuel is burned depends on its carbon content (translated into carbon dioxide emission factor.) Likewise, the amount of useful energy converted from this parallel process depends on the plant heat rate. Given that 3.6 GJ of heat is equivalent to 1 MWh of energy, the remaining factor in the heat rate is simply the plant efficiency rate. Coal-fired stations in the UK have efficiencies between 30 and 40% (Eyre, 1990).

If the plant heat rate is not given, efficiency is approximated by the contribution of fuel to the final discounted cost of electricity generation and the raw fuel price. Hence efficiency expressed in GJ/kWh is derived from dividing the levelised fuel cost in pence/kWh by the raw fuel price of pence/GJ. This calculated efficiency compares realistically with published sources. In the absence of descriptive fuel parameters such as carbon and heat content, all possibilities are considered from a range of values.

Plant efficiency links the fuel to the calculation of the carbon tax component and the fuel component as both require a heat to energy conversion. Plant efficiencies derived from the two reports vary from 25 to 45.45% for coal-fired stations. Plant efficiency is not required for nuclear which is expressed in kWh terms (a crude approximation of the nuclear fuel cycle). Furthermore, carbon taxes do not apply to non-fossil fuel plant.

A.4.8 Load Factor

Fixed costs such as investment and O&M are divided by the actual generating hours to arrive at the pence per kWh figure. This utilisation rate is determined by the scheduled and unscheduled outage rates, in other words, the percentage of time that a plant is scheduled to operate less the percentage of time it is out of service due to planned and unplanned shutdowns for maintenance, refuelling, and other reasons.

Plant utilisation rate is frequently expressed in terms of capacity factor, load factor, and availability factor. The OECD report uses the term load factor as a percentage of total hours in a year, while the UNIPEDE report uses hours in a year to reflect utilisation. The load factor convention is chosen for this paper, and the UNIPEDE hours are divided by 8,760 hours in a year to arrive at an annual percentage figure.

The UNIPEDE study uses an incremental utilisation rate in all scenarios, i.e. the load factor is increased from 45% in the first year to 57% in the second year, and finally 75% for the rest of the life time. On the other hand, the OECD study uses a levelised load factor of 72%, which was derived from averaging the increasing load factors after initial commissioning and the settled down load factor of 75.3%. For simplicity, a constant load factor is used in this pilot study, with the assumption that it represents the levelised lifetime annual utilisation rate. For coal, the sensitivity ranges from 63% to 80%. For nuclear, it is slightly higher, from 65% to 85%.

Using the same O&M cost and the same load factor for every single year of a plant’s lifetime underestimates the cost in the initial years where O&M costs are higher than usual and load factors are lower than usual. Also during the latter years when mid-life refurbishment and additional maintenance costs are necessary, O&M costs are expected to increase with the decrease in load factor.

A.4.9 Escalation Rates

It is unreasonable to expect all costs to remain the same for every single year of plant operation. More likely, the O&M and fuel prices will fluctuate year by year. Instead of computing yearly cashflows, the levelised method uses escalation rates.

A modest range of -1% to 3% per annum is assumed in the sensitivity analysis. For the base case, however, no escalation is assumed.

Yearly escalations do not take into consideration seasonality or daily fluctuations in load. It is assumed that these detailed fluctuations have been averaged in this study.

The effects of incremental carbon tax in accordance to EC legislation and load factors in the normal course of operations can be modelled with escalation rates. No escalation rates are assumed for other parameters.

A.4.10 Life

Economic or amortising life differs from technical life depending on the accounting conventions practised in each country. For discounting purposes, the economic life is used.

The two reports use standard lifetimes of 25 and 30 years to compute the levelised costs. However, in the national calculations, the actual lifetimes used by each country vary from 13 to 45 years. Technical lives are determined by the performance of the plant and are usually longer than economic lives which are used for accounting purposes. At the lower end are Italy (13 years) and Japan (15 and 16 years) for economic life. Since UK falls on the higher side (45 years), the range used for sensitivity analysis in this paper is extended to 50 years.

The economic or amortising life of a project tends to be shorter in the private sector than the public sector, to reflect the degree of risk. A shorter life is preferred in the payback method of appraising projects, allowing costs to be recovered more quickly, albeit at a higher cost to the consumer. The level of business risk is captured in the choice of economic life and the choice of discount rate.

A.4.11 Discount Rate

The UNIPEDE study used a 5% discount rate for two reference lifetimes of 25 and 30 years. OECD used a 5% and a 10% discount rate for a 30 year life. The choice of a discount rate is very particular to the circumstances surrounding a country and a utility. The rates also differ between the public and private sectors.

The former CEGB gave the public sector price of 3.22 pence/kWh (at 1987 prices) for PWR in the House of Commons Energy Committee (1990) inquiry into the cost of nuclear power. This was calculated using an 8% internal rate of return (equivalent to discount rate) over a life of 20 years. The private sector price of 6.25 pence/kWh was calculated by National Power in the run up to privatisation, using a discount rate of 10% to reflect the degree of risk perceived by the private sector. The two reports and this pilot study show that the levelised cost of electricity generation is highly sensitive to the choice of discount rate. The discount rate reflects not only the opportunity cost of capital but also the time value of money, cost of borrowing, and business risk.

The discount rate used in the public sector tends to be much lower than that used by the private sector because regulated monopolies with guaranteed rates of return on capital can obtain low costs of borrowing. The discount rate perceived by the private sector tends to reflect the return on capital that can be invested in various markets, including the return to shareholders on the equity vested in the private utility.

Each country used the same discount rate to calculate its coal and nuclear costs. Across all countries, discount rates varied from 4 to 10%. These rates are based upon market rates, reference rates used in previous energy plans, government advice, and considerations of economic growth and development. It may be argued that higher discount rates should be applied to nuclear projects to reflect the greater investment risk. One study (Virdis and Rieber, 1991) even proposed a discount rate as high as 20%!

There are many ways to determine which discount rate to use. The OECD study suggests some basic approaches to selecting a discount rate:

1) purely policy related aimed at reaching specific social, economic, or political goals in a country,
2) derived on an economic or financial basis, such as
    a) based on the real costs of investment funds over the time scale of the project,
    b) reflecting the opportunity cost of capital at the time of investment as determined by the income it could potentially generate in alternative uses,
    c) based on social time preference reflecting society's desire to protect the interests of future generations, and
    d) some mixture of these concepts.

The selection of a discount rate therefore would depend on the projected rates of inflation, interest rates, and other market based rates.

Ottinger et al (1990) list four different ways to measure future economic benefits and costs with today's benefits and costs:

1) the social rate of time preference,
2) the consumption rate of interest,
3) the marginal private rate of return on investment, and
4) the opportunity cost of public investment.

Aside from financial determinants of the discount rate, Ruth-Nagel and Stocks (1982) warn of the social opportunity cost of capital.

For the moment, a modest sensitivity range of 4 to 15% is used for discounting coal and nuclear.

A.4.12 Consolidating the Range

One of the main interests of this study is to analyse the UK base case and how it varies within the ranges given by the international context. The ranges, as postulated previously, reflect the possible values and include the improbable as well as the probable. It is assumed that the extreme anchors are less likely than the base value, but no attention is paid to the extent of probabilities so far. As argued before, it is more informative to consider all possible values than a fixed percentage about the base value.

It is possible that OECD and UNIPEDE reports may not capture the full range of values for the UK. Comparisons with other published sources are required. Furthermore, the ranges may vary for different periods in time. The ranges captured in January 1987 reflect each country's expectation of the future at that point in time. Many events have taken place since then, and the ranges should be re-adjusted in light of revised expectations of the future. This sense of range is useful even if a seven year update is needed.

The bounds taken from the two reports are converted into sterling using the exchange rates given at the beginning of January 1987, that is, £0.7241 = 1 ECU, and £0.678 = $1.00, i.e. £1.00 = $1.475. The minimum is taken of the lower bounds of both UNIPEDE and OECD studies. Likewise the maximum is taken of the upper bounds. The minimum and maximum are re-adjusted so that the ranges sufficiently surround the UK input parameters to permit a good sensitivity analysis. In addition, annual O&M and fuel escalation rates are assumed. Carbon tax rates are taken from recent EC (Commission of European Communities, 1992) discussions.

Table A.1 gives the revised bounds in £-equivalent.

Table A.1 Consolidated Range

Constant £ @ Jan 1987	**Coal**		**Nuclear**	
FACTOR	Lower Bound	Upper Bound	Lower Bound	Upper Bound
efficiency	25 %	45 %	n/a	n/a
discount rate	4 %	15%	4 %	15%
life	13 years	50 years	13 years	45 years
load factor	63 %	80 %	65 %	85 %
investment cost	475 £/kW	1,211 £/kW	868 £/kW	1725 £/kW
annual fixed O&M cost	6.92 £/kWa	59.74 £/kWa	16 £/kWa	48.8 £/kWa
fuel cost	0.89 £/GJ	2.24 £/GJ	2.10 £/MWh	11.66 £/MWh
O&M escalation	-1 % pa	3 % pa	-1 % pa	3 % pa
fuel escalation	-1 % pa	3 % pa	-1 % pa	3 % pa
carbon tax	0 $/BOE	10 $/BOE	n/a	n/a

While these ranges may appear too large for analysing the sensitivities of UK parameters, it is more justifiable to reduce the range than to expand it later. The analysis has to be qualified in the international context.

A.5 Sensitivity Analysis

One of the main motivations of this study is to understand the factors that influence the cost of electricity generation. The input parameters are assumed constant throughout the plant life to simplify the NPV annuity method of computation. The ranges selected from the UNIPEDE and OECD reports are applied to UK base cases.

A.5.1 Calculation Method

By assuming constant parameters, the average discounted or levelised cost of electricity generation reduces to a method of annuity calculations. A handy spreadsheet function (PMT) returns the annuity or the equivalent constant annual amount that arises for a given number of years. In other words,

Annual Value of a lump sum amount to be spread over a given period at a given discount rate = PMT(discount rate %, years in period, present value of total payment)

This PMT function is useful in determining the equivalent annual amount of investment cost.

$$\text{Cost of electricity generation due to investment} = \frac{\text{PMT(discount rate, life, investment)}}{\text{load factor \% * 8760 hours in a year}}$$

The remaining components of levelised cost are calculated as follows:

$$\text{cost of electricity generation due to O\&M} = \frac{\text{fixed annual O\&M cost}}{\text{load factor \% * 8760 hours in a year}}$$

$$\text{cost of electricity generation due to fuel} = \frac{\text{fuel cost £/GJ * 3.6 heat/energy conversion factor}}{\text{efficiency \%}}$$

for nuclear: fuel cost already expressed in £/MWh

$$\text{carbon tax component} = \frac{\begin{array}{ccccccc}\text{carbon tax} & * & \text{emission factor} & * & \text{heat to energy} & * & \text{exchange} \\ \text{\$/BOE} & & \text{BOE/kg CO2} & & \text{3.6 GJ/ MWh} & & \text{rate £/\$}\end{array}}{\text{efficiency \%}}$$

therefore, the average discounted levelised cost = investment + O&M + fuel + tax

When annual escalation rates for fuel and O&M are introduced, a leveling factor must be multiplied to the existing formula to discount the compounded rates back to present value terms.

The general notation for this leveling factor is $\frac{r(1+r)^T}{(1+r)^T-1} \bullet \frac{k(1-k^T)}{1-k}$

where r = discount rate in %, T = life in years, and $k = \frac{(1+e)}{(1+r)}$ where e = annual escalation rate in %. This is the power expansion of the same expression in sigma notation: $$\frac{\sum_{t=1}^{T} \frac{(1+e)^t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{1}{(1+r)^t}}$$

This calculation method is derived from the levelised bus-bar method explained in IAEA (1984). It is broadly consistent with the methods used in UNIPEDE and OECD, which follow the convention adopted by the Commission of European Communities (EUR 5914 of Commission of European Communities, 1990).

The average discounted cost offers several advantages in comparing future power plants. The ratio of discounted total generation cost over the plant's entire lifetime to the discounted sum of electricity generated over the same period is independent of the date of discounting and the current or future inflation rate. All figures are therefore real, that is, free of inflation.

A.5.2 UK Parameters

Figures for UK Coal and Nuclear were submitted to both UNIPEDE and OECD reports. In the UNIPEDE study, data was provided for two units of 840 MW coal plant, cooled by sea water and equipped with sulphur and nitrogen oxide removal. The nuclear power plant is a 1,155 MW Pressurised Water Reactor (PWR) which includes one reactor of total capacity and two turbo generators of half capacity. Given the date of submission, it is probably the data for Sizewell B. Meanwhile, data for Hinkley C PWR was provided for the OECD study, and the figures for this 1,175 MW reactor are consistent with those submitted in October 1988 to the public inquiry.

Converting the units from ECU and US$ into equivalent £ at the beginning of January 1987 yields the following input values for the UK.

Table A.2 UK Parameters

Constant £ @ Jan 1987	Coal		Nuclear	
FACTOR	UNIPEDE	OECD	UNIPEDE	OECD
efficiency	38.50 %	26.06 %	n/a	n/a
discount rate	8%	8 %	8%	8 %
life	40 years	45 years	35 years	40 years
load factor	74 %	75 %	72 %	75 %
investment cost	891 £/kW	892 £/kW	1,578 £/kW	1,543 £/kW
annual fixed O&M cost	30.59 £/kWa	23.73 £/kWa	26.07 £/kWa	22.10 £/kWa
fuel cost	1.65 £/GJ	0.89 £/GJ	5.36 £/MWh	4.47 £/MWh
O&M escalation	0 % pa	0 % pa	0 % pa	0 % pa
fuel escalation	0 % pa	0 % pa	0 % pa	0 % pa
carbon tax	3 $/BOE	3 $/BOE	n/a	n/a

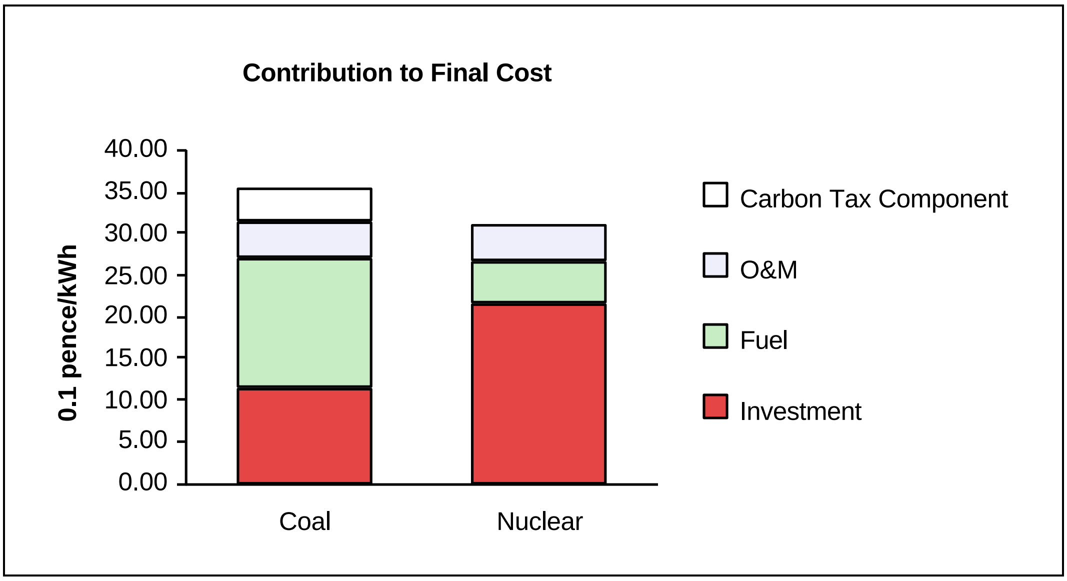
These costs and assumptions were made in 1987 and 1988, after the Sizewell B inquiry, during the Hinkley C inquiries, before privatisation, and before the decision to retain nuclear in the public sector. These figures should be adjusted in light of privatisation in 1990, the demise of new nuclear plant until the 1994 nuclear review and the current “dash for gas” phenomenon. Instead of using 5% discount rate given in UNIPEDE reports, 8% is selected to reflect the onset of privatisation. For purposes of modelling insight, only one set of values is necessary, thus UNIPEDE is retained while OECD values are dropped for the rest of the study. The base costs for the UK figures given above are summarised in table A.3.

Table A.3 Base Costs for the UK

Constant £ @ Jan 1987	Coal	Nuclear
pence/kWh	UNIPEDE	UNIPEDE
investment	1.15	2.15
O&M	0.47	0.41
fuel	1.54	.54
Carbon tax	.40	0
Total Cost	3.56	3.10

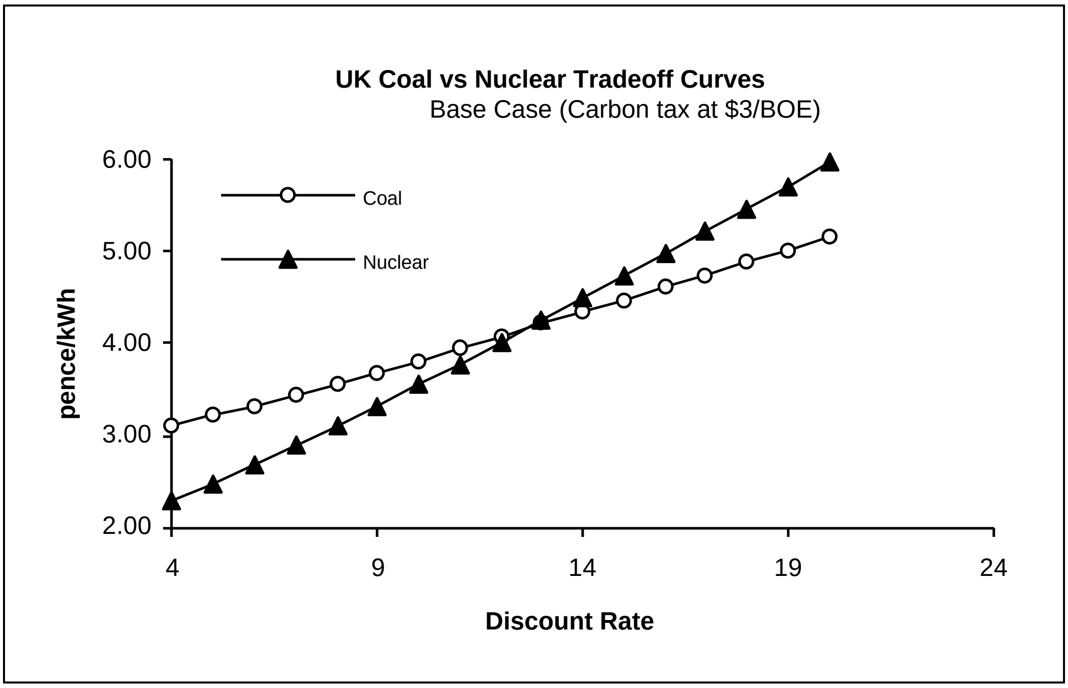
Alternatively the contribution to final cost can be viewed in figure A.6.

Figure A.6 Contribution to Final Cost



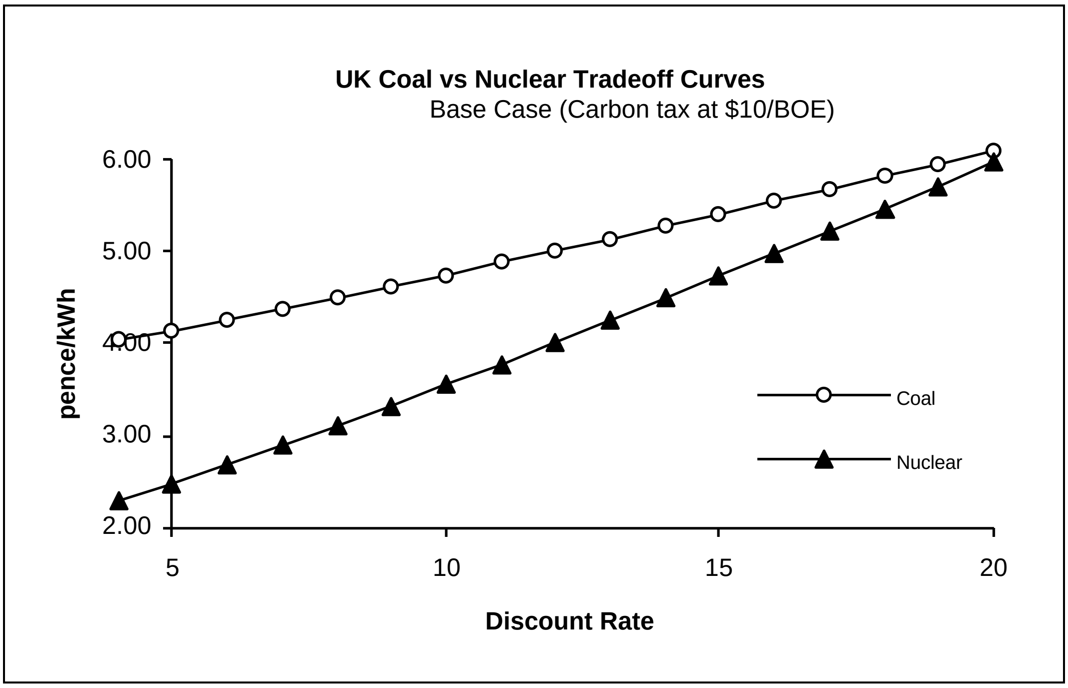
Although initially coal is more expensive than nuclear, the choice of discount rates can change the relative attractiveness of coal and nuclear. Figure A.7 depicts the effects of varying the discount rate. The slope of nuclear plants is steeper than that of coal plants because the investment costs are considerably greater and the magnitude of investment to fuel costs are reversed for the two plants. In the base case with $3 carbon tax applied to coal, the cross-over or breakeven discount rate occurs at approximately 13%. Only then does nuclear become more expensive than coal.

Figure A.7 **UK Coal vs Nuclear Trade-off Curves with $3 Carbon Tax**



If this carbon tax is increased to $10/BOE, then coal will definitely be more expensive than nuclear. As seen in figure A.8, even at the unlikely discount rate of 20%, coal is still more expensive than nuclear.

Figure A.8 UK Coal vs Nuclear Trade-off Curves with $10 Carbon Tax

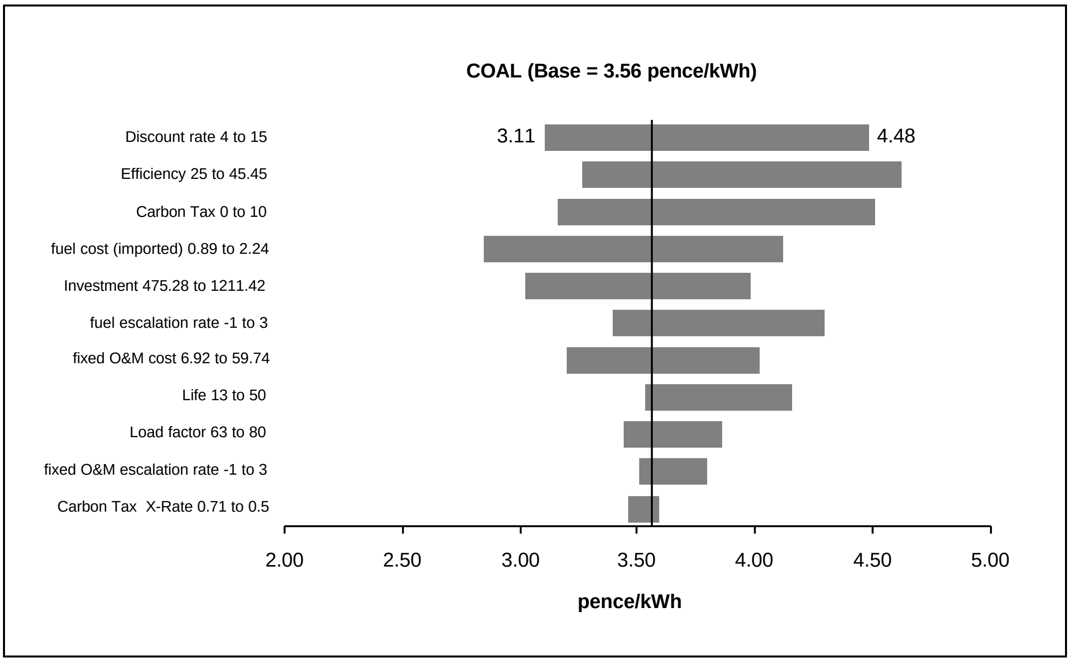


Discount rates are particularly significant in capital intensive projects, like coal and nuclear plants. This is shown in the ascending impact of discount rates on investment costs.

A.5.3 Sensitivity to Range

By applying the derived ranges from the two reports to the calculations of UK base values, it is possible to find the impacts of different factors. The tornado diagram of figure A.9 shows the importance and impact of various costs in descending order.

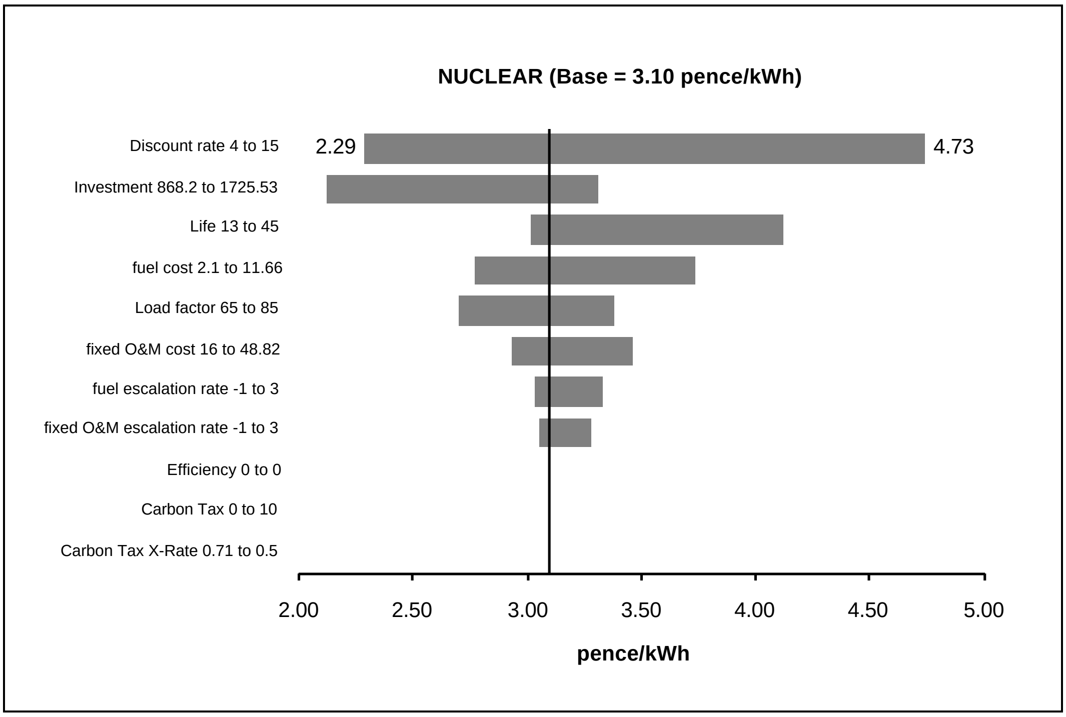
Figure A.9 Coal



Each bar denotes the range of costs computed by varying its corresponding factor without changing the other parameters. In the coal example, lowering the discount rate from the base case of 8% to 4% lowers the levelised cost from 3.56 to 3.11 pence/kWh. Similarly, increasing the discount rate to 15% while keeping all other factors the same, raises the cost to 4.48 pence/kWh.

As discovered earlier, the effect of discount rate accentuates with higher capital costs. The nuclear case in figure A.10 shows the overwhelming importance of discount rate as opposed to investment, life, and other factors. Costs are particularly sensitive to discount rates if investment is high. Fixed O&M costs by comparison has minimal effect. Efficiency rates and carbon taxes do not apply in the nuclear case.

Figure A.10 Nuclear



In reality, discount rates and lifetimes do not fluctuate. These factors are decisions undertaken by the generator. Such controllable variables should not be compared on the same basis as other factors, which are highly affected by external circumstances.

Deterministic sensitivity analysis as a study of variability uncovers the relative importance of factors. Ranges give more information than point estimates. How likely the parameter will take on a value in the range requires the additional dimension of likelihood, frequency, or probability. This additional information of probabilities can be assessed through risk analysis.

A.6 Risk Analysis

A sensitivity analysis tells us how much the output varies with variations in the input values but gives no indication of relative likelihood. A one-way analysis shows the effect of varying one parameter at a time. A two-way analysis shows the result of varying two parameters at a time. Useful insights can be drawn provided the variables are independent of each other. The computation slows down exponentially as more parameters are varied simultaneously, i.e. the curse of dimensionality.

A better representation of uncertainty can be achieved by describing the likelihoods of a variable to take on a specific value. Biases in the input ranges can be represented by probability distributions, where some values are more likely than others. The introduction of probability into this analysis describes the ranges in a more informative way. In the simplest case, every variable has an equal chance of taking any value in a range. Since the previous sensitivity analysis was based on taking a range about a base value, a more informative representation of uncertainty would be the triangular distribution, in which the base value is most likely and has a greater chance of occurring than any other value, with the lower and upper bounds having the least chances of occurring.

A.6.1 Methodology

First of all, factors are distinguished between decision variables and uncontrollable external events. Decision variables are treated in the manner as sensitivity analysis, that is, changing one value at a time, whereas external variables are approximated using probability distributions and varied simultaneously. For this study the discount rate is the only decision variable, the others are external variables. Life is fixed for each type of plant.

As described in chapter 3, the simulation approach to risk analysis is preferable to the analytical approach in circumstances where the input distributions are not symmetric or standard and where computing facilities are available. The Latin Hypercube Sampling (LHS) method was chosen as it performs better than the Monte Carlo method, which tends to take much longer to approximate a given distribution. LHS divides the distribution into equal intervals of the number of iterations selected. Sampling is then taken randomly within each interval, without replacement. This complete coverage of the distribution through stratification avoids the clustering problems found in the Monte Carlo method. LHS converges more quickly than completely random sampling.

The number of iterations required for accurate sampling depends on the number and types of input probability distributions to be sampled. After a certain threshold number, output distributions cannot get any smoother. This can also be validated by using different random number generator seeds. Sampling at 300 iterations gave jagged risk profiles. As a result, iterations were increased to 600 to reach smoothness.

A.6.2 Revised Values

The previous sensitivity analysis already established the ranges and the ranking of important factors. Now it is necessary to use a coherent set of base values for the different plant types. Rather than using base values from both reports, we used values from UNIPEDE, which correspond closely to the values selected in a report by Bunn and Vlahos (1989). Values for combined cycle gas-turbine plants have been approximated. To account for post-privatisation period, discount rates of 8% have been used.

Unlike the previous analysis, the range is considered for the construction cost rather than the investment. This establishes the dependence of the interest during construction (IDC) upon the discount rate and the construction cost. Here, the discount rate is represented by the interest rate. The IDC is made a function of the base IDC, old interest rate and the new interest rate, as follows:

$$\text{new interest during construction} = \text{construction cost} * [(1 + \text{new interest rate})^{\frac{\log (1 + \frac{\text{old interest during construction}}{\text{old construction cost}})}{\log (1 + \text{old interest rate})}} - 1$$

The external variables of load factor, construction cost, O&M, and fuel cost are varied simultaneously according to their probability distributions. These sets of values are analysed for different discount rates and economic lives. For coal and gas, carbon tax is also varied between for the no tax case, $3 minimum tax, and the maximum $10 tax. Again, the incremental effect is not captured in this calculation method.

A.6.3 Nuclear

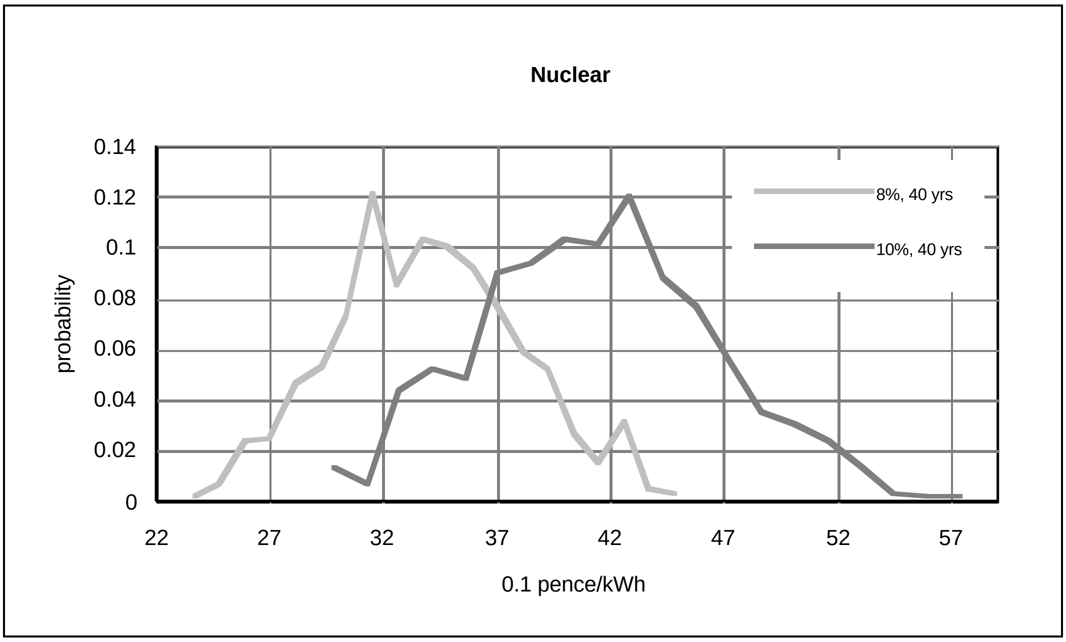
Before the privatisation of the UK electricity supply industry, a 5% discount rate was adequate. Privatisation introduced higher business risk and expected return on projects. To compare nuclear on an equivalent basis, its sensitivity to higher discount rates is required, especially in light of the discussions in the House of Commons inquiry (Energy Committee, 1990) into the cost of nuclear power. Two discount rates at 40 year lives are selected: 8% and 10%. The external variables follow triangular distributions around the base value. Simulation was performed on the following values for nuclear:

Table A.4 Simulation Parameters for Nuclear

Factor	base value (most likely)	treatment	expected value
discount rate	8%	sensitivity 10%	
life	40 years	fixed	
load factor	75%	triang: 65, 85%	75 %
construction cost	1,254 £/k@	triang: 868, 1725	1,282.33 £/kW
provision for decommissioning	10.14 £/kW	triang: 0, 20	10.04667 £/kW
annual fixed O&M cost	26.8 £/kWa	triang: 16, 48.82	30.54 £/kWa
fuel cost	5.4 £/MWh	triang: 2.1, 11.66	6.38667 £/MWh

Note that provision for decommissioning is extracted from investment rather than taken as a lump sum. A triangular distribution of minimum value 0, most likely value 10.14 and maximum 20 should ideally be computed against a lower discount rate from the rest of the project, as is the current practice. Quite a controversy surrounds this, reflecting an important source of risk. Experience with decommissioning of Magnox stations gives evidence of this. Isolating this factor reflects the uncertainty. The result after 600 iterations is depicted in the chart below.

Figure A.11 Risk Profiles for Nuclear



The vertical axis gives the probability or frequency, while the horizontal axis gives the output range expressed in 0.1 pence/kWh. The levelised cost at 10% discount rate halfway overlaps the 8% case. Reading from the chart, we can say with 100% probability that nuclear will not cost more than 4.5 pence/kWh if calculated at the 8% discount rate. Compare this with cost estimates given at the Cost of Nuclear inquiry by Energy Committee (1990): estimates for Hinkley Point C varied from 4.31 pence/kWh to 7.12 pence/kWh at 1987 prices. These were due to the differences in public and private sector assumptions, a so-called protection against uncertainty, and adjustment for inflation. In fact, alternative estimates (other than CEGB) for private sector prices ranged from 4.91 pence/kWh at 8% discount rate to 5.62 pence/kWh at 10% discount rate. Our simulation is not that far off.

A.6.4 Coal

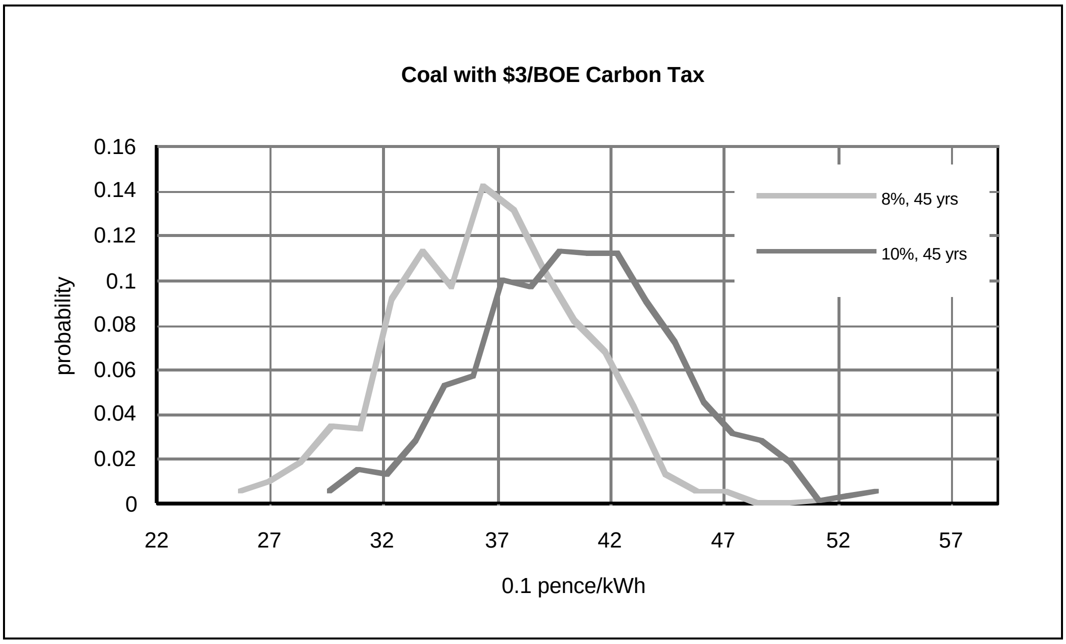
The uncertainty in carbon tax is reflected discretely: $3 tax, $10 tax, or no tax. According to current debate, the tax is expressed in US dollars which has been highly susceptible to exchange rate fluctuations. Therefore an external variable for the exchange rate is built in the model for coal and gas plants.

Table A.5 Simulation Values for Coal

Factor	base value (most likely)	treatment	expected value
efficiency	38.5%	fixed	
discount rate	8%	sensitivity 10%	
life	45 years	fixed	
load factor	77%	triang: 63, 80	73.33 %
construction cost	761 £/kW	triang: 475, 1211	815.6667 £/kW
annual fixed O&M cost	33 £/kWa	triang: 6.92, 59.74	33.22 £/kWa
fuel cost	1.65 £/GJ	triang: 0.8882, 2.23	1.5894 £/GJ
carbon tax	3 $/BOE	sensitivity to no tax	
carbon tax £/$ exchange rate	0.678 £/$	triang: 0.5, 0.714	0.630667 £/$

The risk profiles for coal with $3 carbon tax are shown in figure A.12. At the higher discount rate of 10%, however, more uncertainty is seen in the larger output range. At 8% discount rate, the most likely cost is 3.7 pence/kWh (peak of risk profile). At 10%, the most likely cost lies between 4 and 4.5 pence/kWh.

Figure A.12 Risk Profiles for Coal



A.6.5 Gas

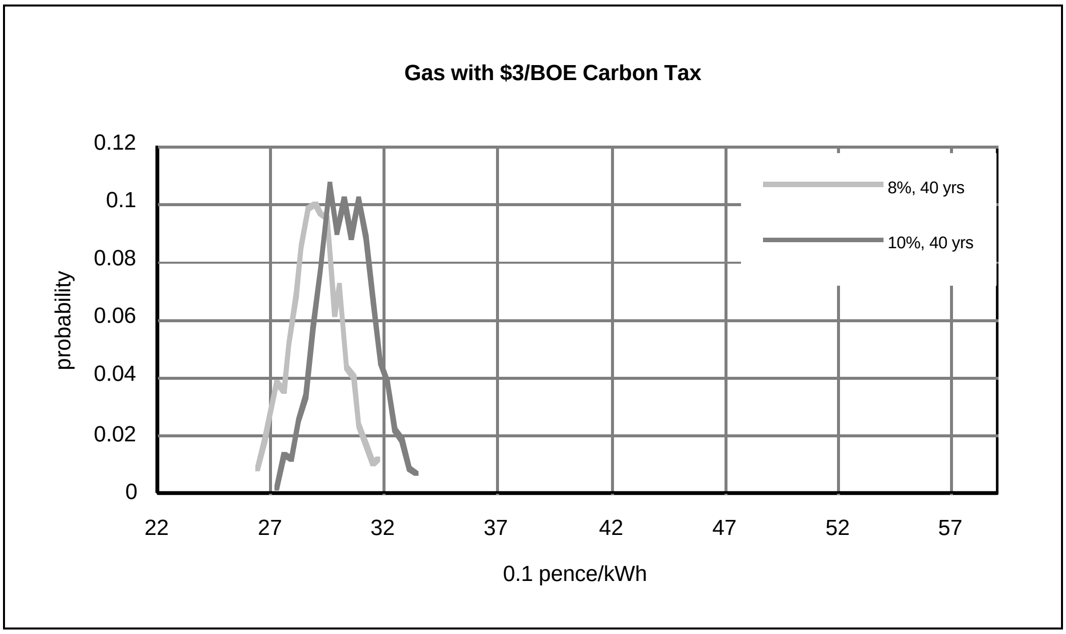
In the last five years, the UK has seen a build-up of natural gas fired plant (CCGT) which have the advantages of high efficiency (typically 45 to 55%), lower carbon dioxide emissions, shorter construction lead time, and modularity of unit size. For these reasons, it is included for completeness. The following base values are taken from Bunn and Vlahos (1989) and the ranges subsequently adjusted to UNIPEDE and OECD reports and modified by current views.

Table A.6 Simulation Values for Gas

Factor	base value (most likely)	treatment	expected value
efficiency	45%	fixed	
discount rate	8%	sensitivity 10%	
life	40 years	fixed	
load factor	80%	triang: 70, 90%	80%
construction cost	400 £/kW	triang: 350, 450	400 £/kW
annual fixed O&M cost	25 £/kWa	triang: 23, 27	25 £/kWa
fuel cost	2.3 £/GJ	triang: 2, 2.6	2.3£/GJ
carbon tax	3 $/BOE	sensitivity to zero and $10 tax	
carbon tax £/$ exchange rate	0.678 £/$	triang: 0.5, 0.714	0.630667 £/$

The greatest uncertainty lies in the fuel price, as natural gas is a premium fuel. With the build up of gas turbines in this country, there is speculation that the fuel price may rise with increasing demand. Up to 60% over capacity is expected in the next decade according to Financial Times (21 Sept 1992). Investment costs are generally very low as its construction period is relatively short compared to coal and nuclear, thus keeping the interest during construction very low. This is the main reason why the costs are not as sensitive to discount rate as the other two types of plants. Risk profiles in figure A.13 show little difference between the 8% and 10% cases, both between 2.7 and 3.3 pence/kWh.

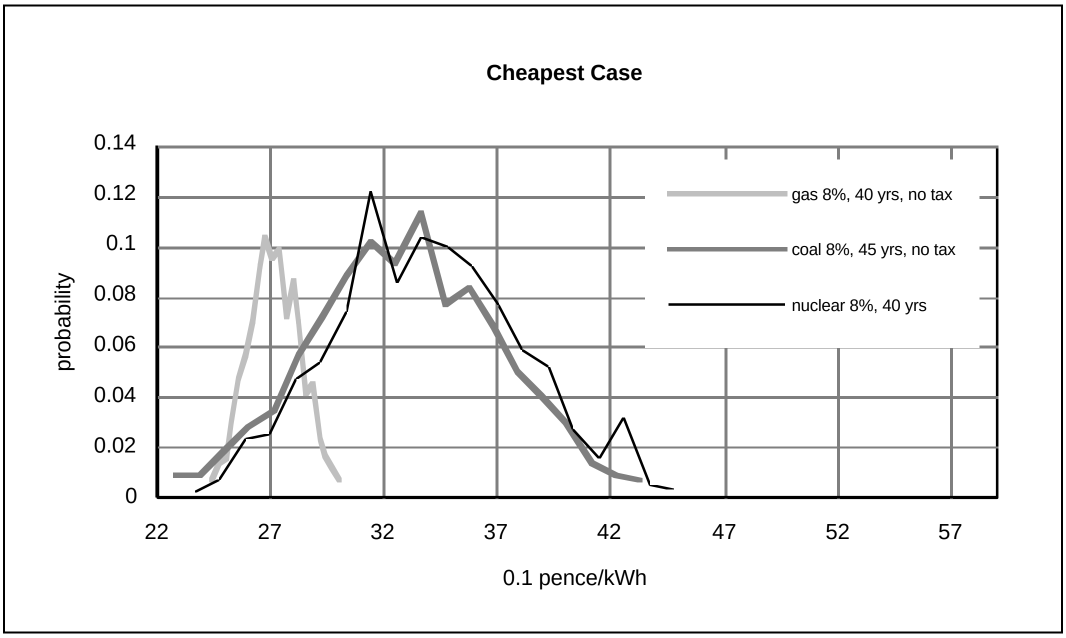
Figure A.13 Risk Profiles for Gas



A.6.6 Trade-off Curves

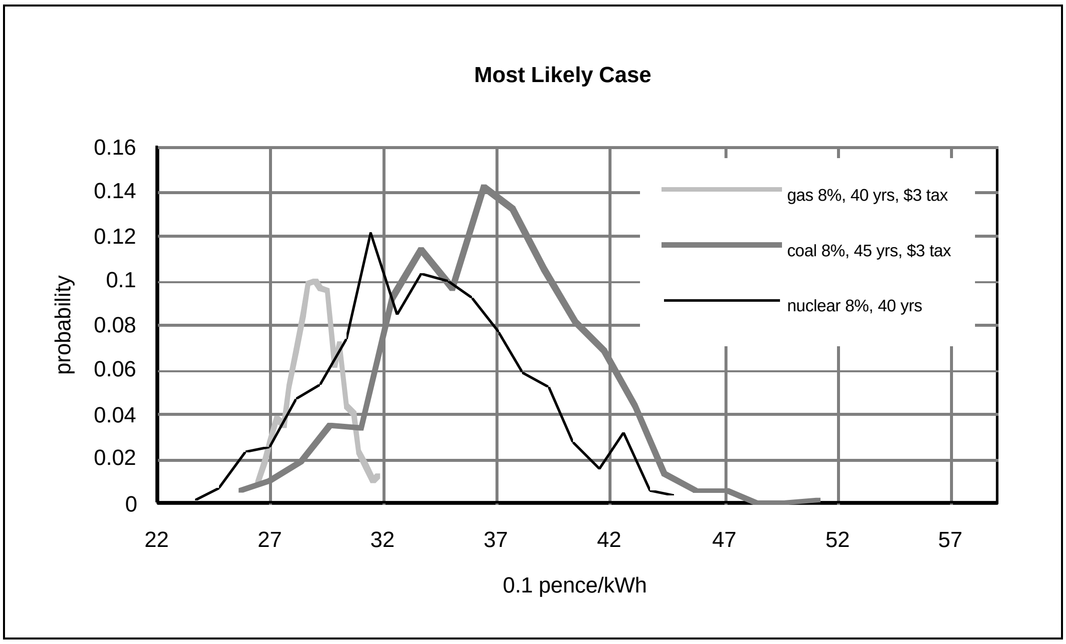
The risk profiles for all three types of plants are combined for a ranking of plant types. Such a comparison is reasonable as all simulations were kept independent. In the base case without carbon tax, gas is the cheapest option, with nuclear and coal in competition. The overlap of risk profiles in figure A.14 shows a small chance that gas may be more expensive than coal and nuclear.

Figure A.14 Trade-off Curves for Coal, Nuclear, and Gas (no tax)



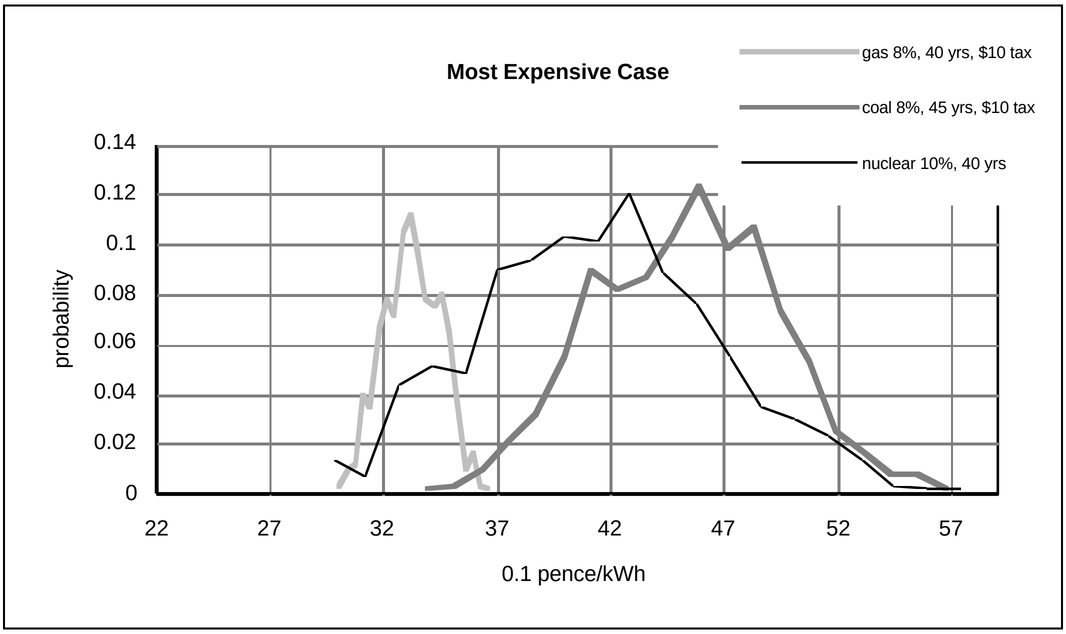
A carbon tax levy such as that proposed by the EC would invariably favour the less polluting plants. However, the high capital cost of tax-free nuclear makes it more costly than gas with tax. The most likely case is presented in figure A.15. Here coal with carbon tax becomes more expensive than nuclear power.

Figure A.15 Most Likely Case



In the extreme, i.e. most expensive case, we apply $10 carbon tax on gas and coal and assume the risks of nuclear power translate into a 10% discount rate. The results in figure A.16 show that the cost of nuclear is much more uncertain than coal as it spreads over a larger range: 3.0 to 5.7 pence/kWh (nuclear) as compared to 3.5 to 5.7 pence/kWh (coal). Coal is still more expensive than nuclear and gas.

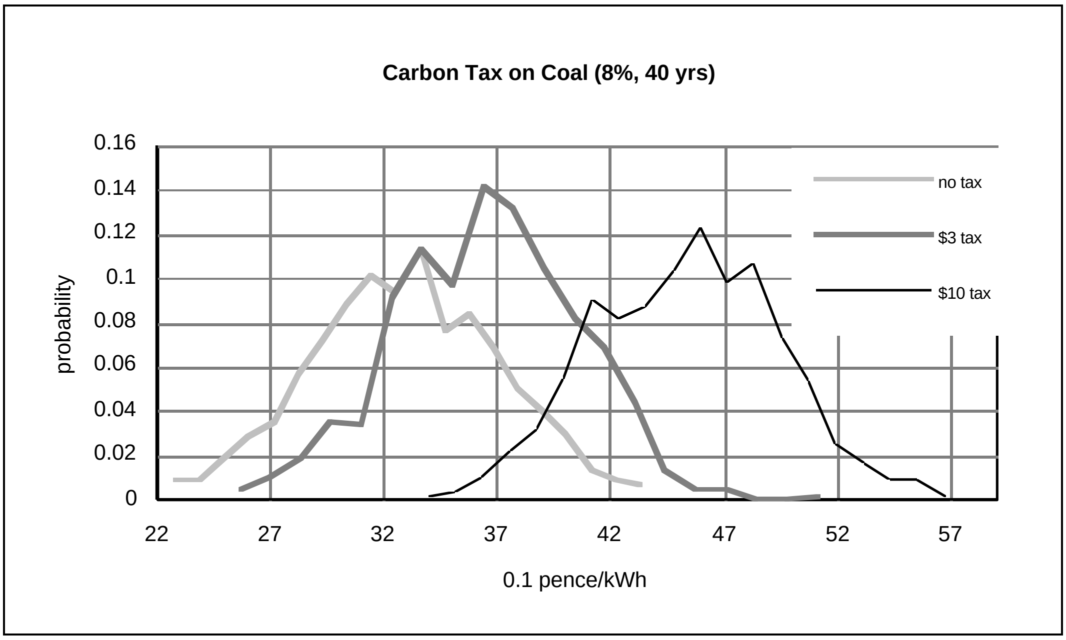
Figure A.16 Most Expensive Case



A.6.7 Impact of Carbon Tax

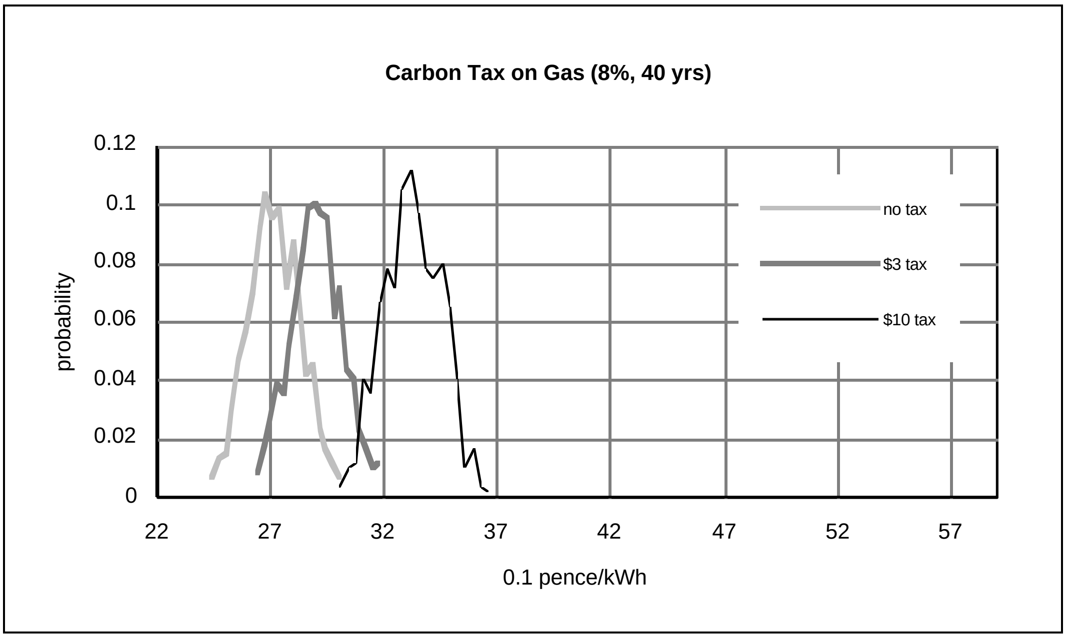
As stated earlier, the incremental nature of the proposed carbon tax is not modelled in this study. The true effect of such a tax lies somewhere between the $3 and $10 case where a fixed amount is levied for every single year of the project. When applied to coal, risk profiles show the significance of a $10 tax. A $10 tax could reasonably double the price of cheap coal-generated electricity, as seen in the following chart.

Figure A.17 Carbon Tax on Coal



The effect of a $10 tax on gas is not as great as that on coal. This is due to the considerably lower emission factor as well as the higher plant efficiency rate. See overlaps in figure A.18.

Figure A.18 Carbon Tax on Gas



A.7 Summary and Conclusions

This study reveals the factors that influence the cost of electricity generation as a precursor to wider issues in modelling uncertainty. A top down approach begins by focusing on the major components of cost and isolating the important drivers.

Base values for UK coal and nuclear are extracted from OECD and UNIPEDE reports and further modified by Energy Committee (1990). The simplified calculation method is consistent with the levelised methods of IAEA, UNIPEDE, and OECD because it uses constant values and minimal escalation rates.

Nuclear, coal, and gas plants are compared. A ranking of technologies shows that gas (CCGT) is cheapest of all three, even with a carbon tax levy.

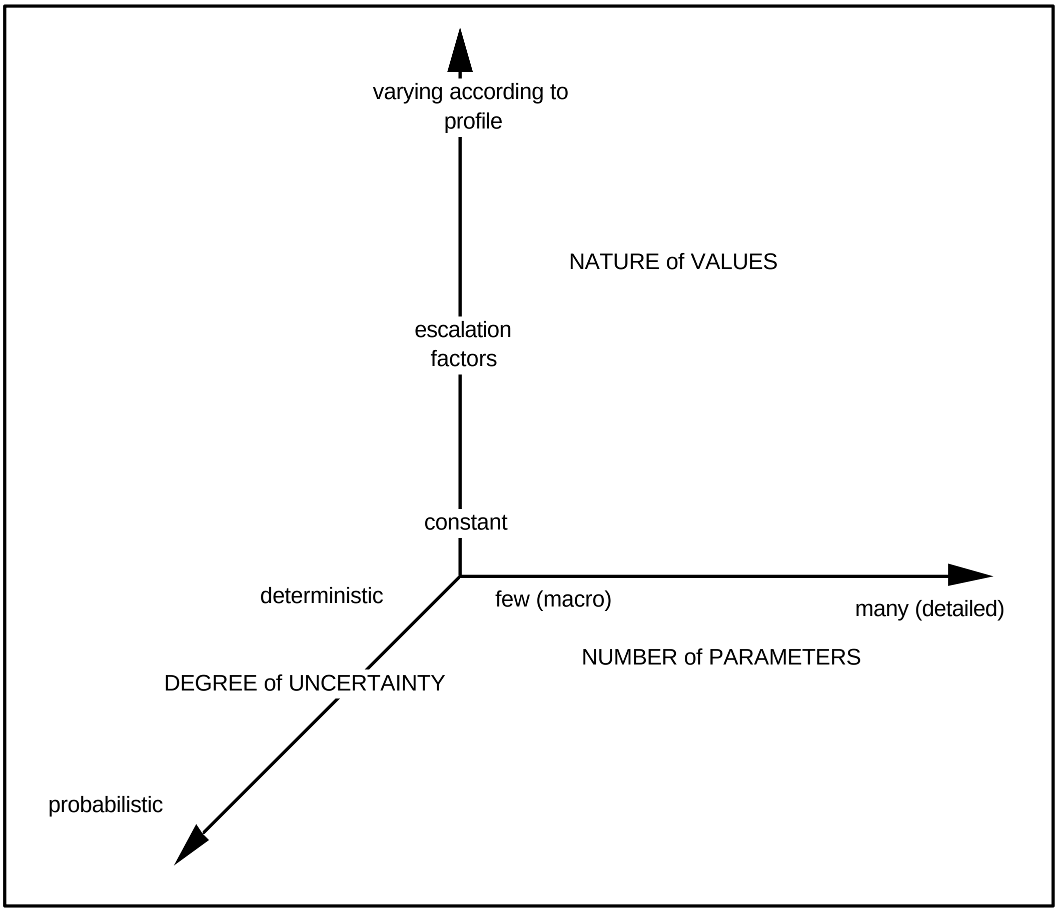
At low discount rates, fuel cost has a greater impact than investment costs. At high discount rates, the reverse is true. In practice, a firm faces the greatest uncertainty in fuel prices.

A simple risk analysis using very crude uncertainty approximations provides greater insight than a rigorous sensitivity analysis which gives no indication of relative likelihood.

Although realistic results are important, this study focussed primarily on methodological issues. To compare with the current scene, the 1987 values used in this study must be updated. We have used risk analysis with the bold assumption of parametric independence which then allowed us to simulate simultaneously. This assumption not only disregards the dependence between the factors but also takes a single staged view of the problem rather than the multi-staged nature of capacity planning.

To achieve a more realistic and complete representation of power plant economics, this study can be extended in three directions, as shown in figure A.19. Greater disaggregation, i.e. decomposing the aggregate variables into their components, not only improves completeness of modelling but also allows a closer examination of detail. As the number of parameters increases, so do the inter-variable dependence and interaction effects. Meanwhile, the nature of values must be extended from the constant to the varying. Most parameters exhibit yearly fluctuations while others vary even more frequently during the operating life of a plant. Seasonality must be incorporated in some form. Ultimately, to understand uncertainty, the level of modelling should be extended in this direction.

Figure A.19 Modelling Directions



Disaggregation means breaking down large components into smaller ones for greater manageability or to achieve a greater level of detail. For example, to understand investment cost, we must look at its components of construction cost, interest during construction, desulphurisation or denitrification fittings if applicable, provision for decommissioning, and other capital costs. Similarly, operations and maintenance should be evaluated against its fixed and variable components, unlike the assumption of fixed O&M in this study.

Interest during construction can be viewed as a financing cost or an investment cost as it reflects the cost of capital. The interest rates used in the calculation depend on the interpretation and the subsequent risks involved. If business risk is not incorporated in the discount rate, it should be incorporated elsewhere. The interest rate also depends on the size and economic life of the project. The construction period affects the size of the IDC, particularly in the form of construction cost draw-downs. Interest during construction can be further analysed by varying the interest applied to the investment schedule prior to the commissioning date.

Actual utilisation of a power plant depends on its planned and unplanned down time and the merit order. Strictly speaking, utilisation should come from the combined effects of availability and load factor. In this case, load factor is given by the merit order of operations, typically determined by the fixed and variable costs. Ignoring emission constraints, plants with high fixed costs and low variable costs are loaded before those with low fixed cost but high running costs. Alternatively, we can introduce demand by way of load distribution curves, which are then aggregated and averaged to give load duration curves.

The privatised power companies have the additional objective of profit maximisation. It is in their interest to take every advantage of capital allowances, tax shields on depreciation, and inflation accounting. Although this study has examined the economics net of inflation and taxes, it is worthwhile to introduce corporate tax and inflation rates to see the effects on cashflow planning.

From a technical perspective, this study has restricted the power plants to “typical” or “generic” ones according to the type of fuel used. In reality, there is no “generic” coal plant. Different grades of coal have different levels of carbon, sulphur and heat contents and , in turn, burn at different efficiencies and release different quantities of CO_2, SO_X, and other gases. Consequently, the resultant carbon taxes will vary. Plant efficiencies are also related to operational efficiencies and retarded by FGD and other cleaning equipment.

The uncertainties at the back end of the nuclear fuel cycle and the last stage of decommissioning are much cause for concern. This decade will witness the decommissioning of the older nuclear reactors in the UK. Analysis into the treatment of provision for decommissioning is therefore important as it makes up a great proportion of total costs, which carry future risks and responsibilities.

With the exception of fixed annual escalation rates, all values have been kept constant throughout the economic life of the plant. This is an unrealistic assumption as it does not allow fluctuations in load factor and fuel prices. To account for these fluctuations, the levelised cost approach must be expanded to handle yearly cashflow calculations so that, at the very least, yearly fluctuations can be incorporated. Some parameters exhibit annual patterns, e.g. seasonality in availability. Some vary constantly, e.g. spot fuel prices. Utilisation depends on demand which varies according to the season and time of day.

Economies of scale is a non-linearity that can be modelled by quadratic functions. Following a detailed causal analysis and an understanding of the inter-relationship between factors over their entire ranges, these effects can be modelled by fitting suitable equations.

This pilot study has established the feasibility of model replication of sensitivity and risk analyses with available desk-top computing tools. The incremental manner in which details are added and complexity increased maintains the modelling at a comfortable and manageable level.

By extracting values from different international sources, we are able to get a range of possible values for each factor, which not only improves upon the traditional point estimates but also gives us insight into causality and broader perspectives. However, we had to take a view on which base values to use and which extreme values to include. These international reports, being also seven years out of date, do not give us adequate detail to the economics of UK plant.

Next, we used sensitivity analysis to rank the factors, thus allowing us to focus on the important and highly sensitive variables, such as discount rates and capital cost. Tornado diagrams are helpful aids for this analysis even though the ranking depends on the base values and the extreme values. During this process, there emerged a need for guidelines on the number of factors sufficient for an analysis such as this. Without detailed knowledge of the relationships between factors, we are not able to utilise the two way sensitivity analysis.

Finally, we applied risk analysis to get the extra dimension of likelihood. The two-dimensional risk profiles allowed us to evaluate the stochastic dominance of different types of plants, although at this stage only the risk profiles. However, use of probability distributions introduced several new issues. Although we have used triangular distributions, the base and extreme values can equally define the finite normal, the beta, or the uniform distribution. We need to analyse which distributions are more appropriate or otherwise develop a distribution selection criteria. For factors without extreme bounds, it is unclear whether we should set a fixed percentage around the base values or a variable percentage. Our assumption of total independence allowed model simplification and avoided having to consider multi-variate probability distributions. Dependence of factors led to correlations between distributions. Using the Latin Hypercube sampling method, we determined that 600 iterations on one random seed was sufficient to get smooth output profiles. We need to validate this by testing with other random seeds and more iterations. Finally, we have approached this case study from a neutral position, whereas the actual case study would undoubtedly be assessed very differently by the regulator, Nuclear Electric, major generator, independent power producer, and the consumer.

Realistic modelling requires a thoroughness of approach, which is examined along the lines of financial, technological, and modelling. The financial aspects relate to ***isolating the discount rates*** used in calculating the interest during construction, provision for decommissioning, and the other costs. In other words, the cost of capital requires a much closer examination into what it represents. In the private sector, corporation taxes and inflation impact ***cashflow*** management, which cannot be ignored. Business ***risks*** can also be modelled through a redefinition of the treatment and use of the discount rate. The technology issues relate to the treatment of utilisation rates, fuel types, plant types, etc.

The three directions of increasing the number of parameters, varying the values, and increasing the uncertainties represented in the problem are a mere framework for a thorough approach. Thoroughness lies in the consideration of all significant variables, close representation of reality, and systematic treatment of uncertainty. Throughness is a means of achieving greater completeness in modelling. However, this comes at the expense of manageability and tractability. It may be necessary to use other techniques to facilitate a greater level of detail and modelling capability. In this respect, model synthesis may provide the answer to greater completeness and manageability, i.e. to meet the conflicting criteria of comprehensiveness and comprehensibility.