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A Probabilistic Approach to Levelised Cost Calculations For Various Types of Electricity Generation

Paper by Colin Gibson

Note: Items in red refer to issues where further investigation is known to be needed.

SUMMARY

This paper outlines a probabilistic approach to the calculation of levelised costs for various types of generation. It develops a base case for each type of generation then uses it as the basis for the probability analysis. From this analysis, a graph of levelised cost against cumulative probability (an 'S'-curve) can be constructed for each type of generation that clearly shows not only differences in levelised cost but also the degree of uncertainty about the central estimate.

The author recognises the lack of empirical data for some types of generation particularly with regard to the probabilities that should be assigned to the various levels for each input parameter. However, the methodology should be seen as an aid to provoking debate to draw out the best engineering judgement regarding these input parameters. At various places in the paper there are indications (in red)of areas where the author would welcome further debate and input.

Levelised costs, whilst being a useful guide in considering long-term energy policy, are not a complete substitute for total system cost studies in planning a power system.

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1. Introduction

1.1 For these studies, the levelised cost (See Appendix 1) of a type of generation is taken as all the costs as seen by the customer discounted with regard to time, divided by the energy output also discounted with regard to time. The discount rate used is the average weighted cost of capital. The costs include, for intermittent generation, all the costs of delivering to the customer the same ‘product’ in respect of Security of Supply and frequency control of non- intermittent generators. If the energy output is considered a proxy for income, levelised cost is the reciprocal of the commonly used Profitability Index method of ranking projects when only limited funds are available

1.2 This probabilistic approach is not new to the GB electricity supply industry. The author first used it in the late 1970s in assessing a large pumped storage plant in Scotland. In that case the relevant output parameter was total system cost: in this instance it is levelised cost.

1.3 This approach has a great advantage over the scenario approach that simply shows a possible range of outcomes without attaching probabilities to these outcomes occurring. The method used in this paper allows the derivation of the probability of the output parameter (levelised cost) falling within various ranges.

1.4 The initial studies consider the following types of generation: -

(a) Nuclear
(b) On-shore wind
(c) Off-shore wind
(d) Tidal Barrage (Severn)
(e) CCGT
(f) Coal without Carbon Capture and Storage (CCS)
(g) Coal with CCS, Advanced Supercritical plant (ASC) and Flue Gas Desulphurisation (FGS)
(h) Coal with CCS and Integrated Gasification Combined Cycle (IGCC)

In a second phase of studies it is intended to consider: -

(a) OCGT
(b) Tidal stream
(c) Conventional Hydro
(d) Pumped Storage
(e) Biomass

It is recognised that data on both conventional hydro and pumped storage will be particular to the sites considered and, therefore, not necessarily generally applicable.

2. General Method

2.1 For each type of generation a basic model was produced using central estimates from a variety of sources.

2.2 These basic models were used to determine the sensitivity of the levelised cost to10% variations in each of the input parameters. In order to limit the number of studies for each type only those input parameters to which the levelised cost was most sensitive were used as input variables – the Key Variables. [Further work is required to make this part of the process automatic – perhaps by the use of a Monte-Carlo technique if continuous functions could be developed for the input parameters. The quality of the input data currently does not justify this approach, but automation of this part of the method would allow all input parameters to be varied.] A step in this direction has been taken in that a macro has been developed for each spreadsheet that will automatically produce an output for any set of input parameters. With small modifications to the macros, this development will allow all input parameters to be considered as variables in the probabilistic studies without a large increase in the work involved.

2.3 For each of the variable input parameters, central (from the base study), high and low values were selected and probabilities assigned to each of these values. The probabilities of each possible combination of variable input parameters were determined, and for each combination, the levelised cost was calculated.

2.4 An ordered list of levelised costs (along with the probability of each cost occurring) was structured. Then, by cumulating the probabilities, the probability of the levelised costs being less (or greater) than a specified value can be calculated. Plotting this gives a cumulative probability characteristic (or S-Curve) for each type of generation. A polynomial trendline of the cumulative probability was drawn in each case. [Further work – it would be interesting to know if including more input variables produced a significant improvement over the trendline.]

2.5 A point on the S-Curve represents the probability that that cost will be less than this value. For example the 0.1 cumulative probability means that there is a 10% probability that the actual cost will be less than this value. The 0.9 value is that there is a 90% chance that the actual cost will less than this value and hence that the chance that it will be greater than this value is 10%.

2.6 These S-curves can be used in a number of ways. The slope of the curve gives an indication of the uncertainly of the levelised cost. Placing all the S-curves on a summary chart allows for easy comparisons between types of generation both in absolute values of levelised cost and uncertainty. Also, for example, the range of levelised cost covering the central 80% probability can be read off the chart.

2.7 A macro has been provided for each spreadsheet to calculate automatically the levelised cost for all combinations of key variables and to calculate the cumulative probabilities. This approach can be extended to cover a wider range of key variables and an increased number of probabilities per key variable.

3. On-shore Wind

3.1 The Basic Study for On-shore Wind.

3.1.1 The basic model used the following **Finance** input parameters : -

(a) A Return on Equity of 12% real.

(b) A Cost of Debt of 5% real after tax. (Is this too high? It implies 8% nominal, and about 11% nominal before tax. Citigroup used 4.5% real after tax for nuclear. A reduction to 4.5% real after tax would reduce the levelised cost by £2/MWh)

(c) Gearing of 48%. This gives a resultant discount rate of 8.64%. This is about the maximum gearing that would be acceptable to providers.

(d) An Investment Rate of 2.5% real was assumed for the fund to make any payments at the end of the operating life.

3.1.2 The central figure for **Capital Cost** of £152m for a 100MW wind farm was taken from the Mott MacDonald /DECC study (central estimate for a NOAK page 100). An Incidence of Expenditure of 50% in each of years –1 and –2 was used (engineering judgement).

3.1.3 The central figure for **Operating Costs** of £3.4m/year was taken from the Mott MacDonald /DECC study for a NOAK. The range was £2.7m/year to £4.5m/year.

3.1.4 A median **Load Factor** of 25% was used based on the same data base as the Stuart Young study for The John Muir Trust. It is recognised that this data base is limited but it is the best available for the UK. This will be up-dated as more data become available. The Mott MacDonald/DECC study uses a central figure of 28%, with a low of 25% and a high of 31%.

3.1.5 An **Operational Life** of 20 years is assumed.

3.1.6 The extra system cost of accommodating the **intermittency of wind in an operational timescale** was taken from the Parsons Brinkerhoff paper Powering the Nation as £16/MWh of wind generation. This figure is for a significant proportion of wind generation, and the figure will vary in a non-linear way. (Does this include such costs as extra response and/or reserve to cover the possible loss of large amounts of wind generation when wind speeds increase from maximum output to tripping levels?)

3.1.7 **Back-up generation** to provide the same level of contribution as thermal plant to Security of Supply is assumed provided by OCGTs costing £0.5m/MW of Capex. Wind generation has been given a credit of 8% of installed capacity as in the EOn submission to the House of Lords Inquiry. Only capital charges are included.

3.1.8 The extra cost for **Transmission** to connect generation in the north of Scotland to the main load centres in the south of England is based on the latest costs for the Beauly-Denny line of some £600m. The Public Inquiry was based on 2100MW of generation in the North West. This would result in an additional £15.5/MWh of levelised cost. However, this power has to be transferred to a notional point on the transmission system just north of London and aggravates existing limitations to the general flow of power north to south. The distance from Denny to this notional point is some four times the distance from Beauly to Denny. A large assumption is made by simply doubling the levelised cost of Beauly-Denny to £31/Mwhr. (There is further work required on this – informal discussions with National Grid indicate that study of their papers Operation of the Transmission Network in 2020 and the Seven Year Statement would be useful. Also, the author holds the view that had all the capital costs of reinforcing the GB system [as opposed to the capital costs of Beauly-Denny] been compared to the costs of constraints, then the Beauly-Denny line would not have been justified on economic grounds. Neither does the author agree with the load flow input data used in the papers presented to the Public Inquiry. This used 60% of the installed wind generation capacity – a 'reasonable' level, which is that specified in the Standard, would be the median level of about 20% of installed capacity. These changes would have a significant lowering effect on the cost of transmission.)

3.2 Sensitivity of the Basic Study for On-shore Wind

3.2.1 The sensitivity of the output parameter of levelised cost was tested for 10% variations in the various input parameters with the following results : -

	Levelised Cost	% Variation on £187/MWh
Reduce required return on equity	181	-3
Reduce cost of debt	185	-1
Increase gearing	187	0
Increase load factor	172	-8
Reduce Opex	186	-1
Increase Transmission discount rate	187	0

Increase wind generation capex	197	5
Increase OCGT capex	190	2
Increase Transmission capex	190	2

3.2.2 It is noted that Return on equity, Cost of Debt, and Gearing may not be independent variables, but all influenced by the perceived risk of the project.

3.2.3 By far the two most sensitive variables are Load Factor and the Capital Cost of the wind generators. Therefore, it was decided to examine these in the first studies.

3.3 The Probabilistic Study for On-shore wind

3.3.1 For **Load Factor,** the data was taken from the National Grid's Balancing Mechanism data base for the months November 2008 to December 2010. (This is the same data base as used in Stuart Young's paper for the John Muir Trust.) It results in 15 12-month periods which is recognised as being very limited, but it is probably the best available. It is for transmission connected wind farms only. The 15 12-month periods fell into the following ranges : -

Load factor Range %	Occurrences	
	Number	%
20-22	5	33
22-24	3	20
24-26	2	14
26-28	2	13
28-30	3	20

From this, the data used for the probability study was a 14% probability of the central figure of Load factor being 25%, the low figure of 22% load factor having a probability of 53%, and the high figure of 28% Load Factor having a probability of 33%. (As more data become available there would be value in considering five values of Load Factor since this is the most sensitive input parameter.)

3.3.2 The range of figures for the **Capital Cost** of wind generation was taken from the Mott MacDonald / DECC paper. This gives a central figure for a 100MW wind farm of £152m. The low figure is given as £133.5m and the high figure as £168m. In all cases, the figures used are excluding transmission. No probabilities for the range are given in the MM / DECC paper, so probabilities were simply assigned as follows : -

Low	£133.5m	20% probability
Central	£152m	60% probability
High	£168m	20% probability

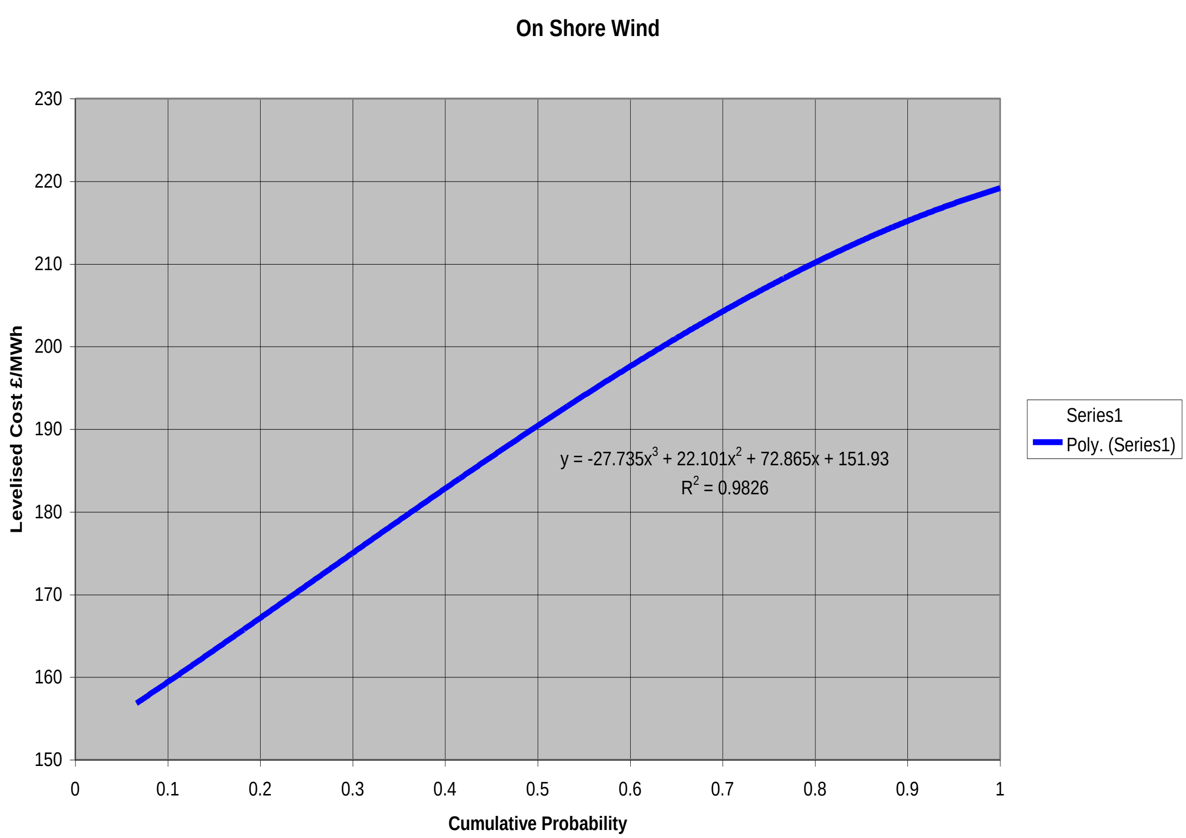
(Future work should include an examination of forecast capital costs and actual outturns.)

3.4 Results of the Probabilistic Study of On-shore wind

3.4.1 The results are contained within the Ons worksheet.

3.4.2 The median value of the trendline is £190/MWh, and the central 80% of probable outcomes covers the range £160 – 215/MWh.

3.4.3 The resultant 'S – curve' is shown below.



4. Off-shore Wind

4.1 The Basic Study for Off-shore Wind.

4.1.1 The basic model used the following **Finance** input parameters: -

(a) A Return on Equity of 12.5% real.

(b) A Cost of Debt of 6% real after tax.

The financing costs of have been taken to be slightly higher than on-shore wind to reflect the extra risk of off-shore projects.

(c) Gearing of 48%. This gives a resultant discount rate of 9.38%. This is about the maximum gearing that would be acceptable to providers.

(d) An Investment Rate of 2.5% real was assumed for the fund to make any payments at the end of the operating life.

4.1.2 The central figure for **Capital Cost** of £284m for a 100MW wind farm was taken from the Mott MacDonald /DECC study (central estimate for a NOAK page 101). An Incidence of Expenditure of 60% in year –2 and 40% in year –1 was used. This is based on engineering judgement, and should be updated in the light of experience.

4.1.3 The central figure for **Operating Costs** of £15.2m/year was taken from the Mott MacDonald /DECC study for a NOAK. The range was £13.1m/year to £17.4m/year.

4.1.4 For **Load Factor** the Mott MacDonald/DECC study uses a central figure of 41%, with a low of 38% and a high of 45%. This is an increase of 46% on the Mott MacDonald/DECC for on-shore. This looks very high considering the significant problems of carrying out maintenance off-shore to deliver a high plant availability. An increase of some 30% over on-shore would seem more prudent at this stage until better actual data are available. This gives a median **Load Factor** of 32%.

4.1.5 An **Operational Life** of 20 years is assumed.

4.1.6 The extra system cost of accommodating the **intermittency of wind in an operational timescale** was taken from the Parsons Brinkerhoff paper Powering the Nation as £16/MWh of wind generation. This is the same as on-shore wind.

4.1.7 **Back-up generation** to provide the same level of contribution as thermal plant to Security of Supply is assumed provided by OCGTs costing £0.5m/MW of Capex.

Wind generation was given a credit of 8% installed capacity as in the EOn submission to the House of Lords Inquiry. Only capital charges are included. This is the same as on-shore wind.

4.1.8 The extra cost for **Transmission** to connect generation in the north of Scotland to the main load centres in the south of England is taken to be the same as for on-shore. That is the capital cost of off-shore transmission is contained within the total capital cost of the project.

4.2 Sensitivity of the Basic Study for Off-shore Wind

4.2.1 For the off-shore study, the same two variables were considered as for on-shore i.e. Load factor and Capital Cost.

4.3 The Probabilistic Study for Off-shore wind

4.3.1 For **Load Factor,** the same data base as for on-shore wind was used, but in this case the values for load factor were increased by 30%, with the probabilities attaching to the figures remaining the same.

4.3.2 The range of figures for the **Capital Cost** of wind generation was taken from the Mott MacDonald / DECC paper. This gives a central figure for a 100MW wind farm of £284m. The low figure is given as £232m and the high figure as £335m. In all cases, the figures used are excluding transmission. No probabilities for the range are given in the MM / DECC paper, so probabilities were simply assigned as follows: -

Low	£232m	20% probability
Central	£284m	60% probability
High	£335m	20% probability

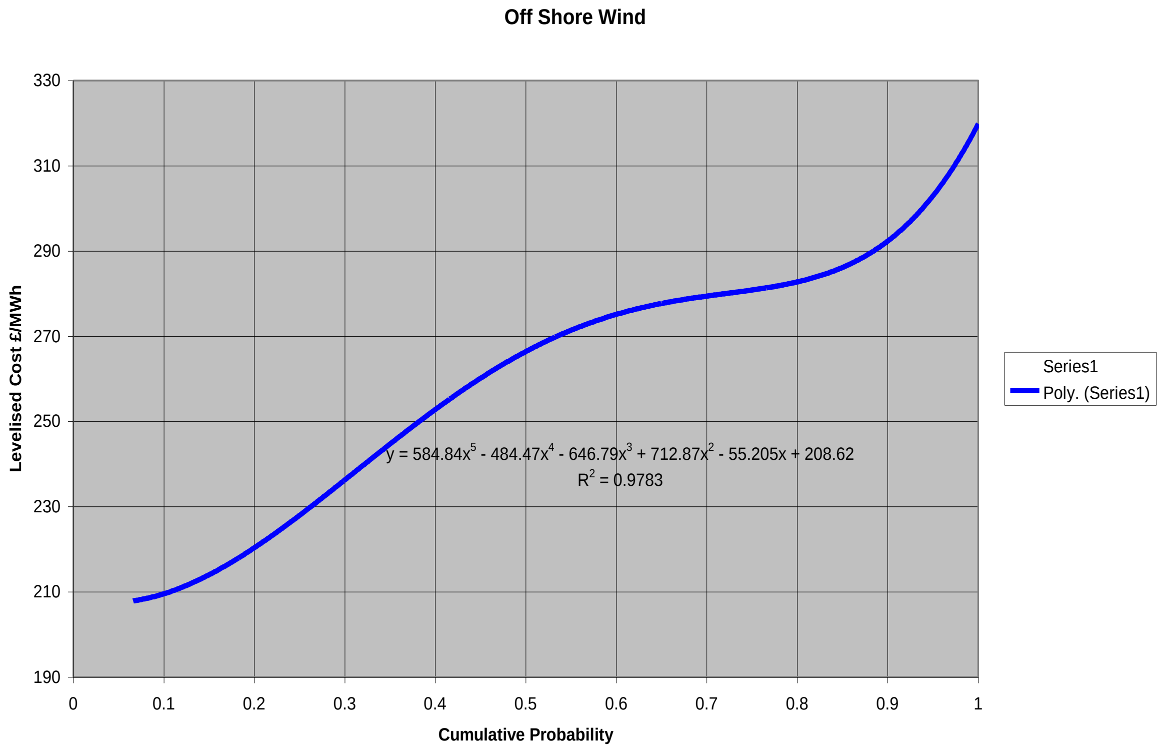
(Future work should include an examination of forecast capital costs and actual outturns.)

4.4 Results of the Probabilistic Study of Off-shore wind

4.4.1 The results are contained within the Offs Worksheet.

4.4.2 The median value of the trendline is £265/MWh, and the central 80% of probable outcomes covers the range £210 - 293/MWh.

4.4.3 The resultant 'S – curve' is shown below.



5. <u>Nuclear</u>

5.1 The Basic Study for Nuclear

5.1.1 The basic model used the following **Finance** input parameters : -

(a) A Return on Equity of 12.5% real.
(b) A Cost of Debt of 4.5% real after tax.
(c) Gearing of 50%. This gives a resultant discount rate of 8.5%. The financing costs have been taken from the Citigroup report.
(d) An Investment Rate of 2.5% real was assumed for the fund to make any payments at the end of the operating life.

5.1.2 This study uses two sources for information on **Capital Costs.** The Mott MacDonald/DECC paper gives a central figure for the construction of a 1600MW station (1520MW sent out) of £4,500m. This study considers a NOAK so no pre-development costs are included. The Citigroup paper considers eight stations – some completed, some still under construction. The average figure works out at $m4.2/MW (£m2.9/MW). So, for a 1600MW station the cost would be £4,587m – very close to the Mott MacDonald/DECC figure. The **Incidence of Expenditure** is spread evenly over the 5 years pre-commissioning.

5.1.3 The central figure for **Operating Costs** of £118.5m/year was taken from the Mott MacDonald /DECC study for a NOAK.

5.1.4 The Mott MacDonald paper gives availability figures that look rather high – central 90.8%. The Citigroup paper (quoting EdF) gives actual figures that average 81.5% in the early years and 85% for follow on years. This study uses **Load Factors** of 81.5% for years 0-5, and 85% for years 5 – 60. Since this is a base load station, load factor has been assumed to be the availability. It is recognised that a full system study may show load factors slightly below availability.

5.1.5 A **Station Life** of 60 years has been assumed.

Future work should consider the cost of replanting part way through the 60 year life e.g. control systems, steam chests etc.

5.1.6 The Mott MacDonald report does not give **Fuel Costs,** but gives a levelised cost of fuel at 10% discount rate of £5.3/MWh but makes no mention of decommissioning or handing the final fuel charge. This study uses £5/MWh for fuel, but adds in the following costs for **Waste, Storage, and Decommissioning: -**

On-site waste costs £15.2m/year
Off-site storage costs £13.2m every 10 years
Waste disposal (final fuel charge) £276m at decommissioning
Decommissioning £636m Present Valued to final operations year

5.1.7 The basic study gave a levelised cost of £60/MWh

5.2 Sensitivity of the Basic Study for Nuclear

5.2.1 The sensitivity of the output parameter of levelised cost was tested for 10% variations in the various input parameters with the following results : -

	Levelised Cost	% Variation on £60/MWh
Capital Cost	65	+8
Investment Discount Rate	60	0

Return on Equity	64	+7
Reduce cost of debt	62	+3
Gearing	58	-3
Load Factor	57	-5
Operating costs	61	+2
Fuel Cost	61	+2

5.2.2 From this, Capital Cost, Return on Equity, and Load Factor were taken as the independent key variables.

5.3 The Probabilistic Study for Nuclear

5.3.1 The range of figures for the **Capital Cost** for nuclear was taken from the Mott MacDonald / DECC paper. This gives a central figure for a 1600MW nuclear station of £4500m. The low figure is given as £3800m and the high figure as £5000m. In all cases, the figures used are excluding transmission. No probabilities for the range are given in the MM / DECC paper, but the range of costs in the Citigroup paper allow a rough assignment of probabilities as follows : -

Low	£3800m	15% probability
Central	£4500m	50% probability
High	£5000m	35% probability

5.3.2 There is little hard statistical data on the probability of variations in **Equity Return,** but since this is a significant variable a range of +/- 1 percentage point has been considered with a probability of 20% assigned to the low and high values.

5.3.3 For **Load Factor,** the low figure from the Citigroup (EdF figures) range of 82% has been used. The high figure of 87.5% is from the CEGB 1985 paper on Security of Supply. However, there is little information on current plant available. The 1985 paper assumed the probability distribution for availability is ‘normal’ with a standard deviation of 3.75%. This has been used to give the following : -

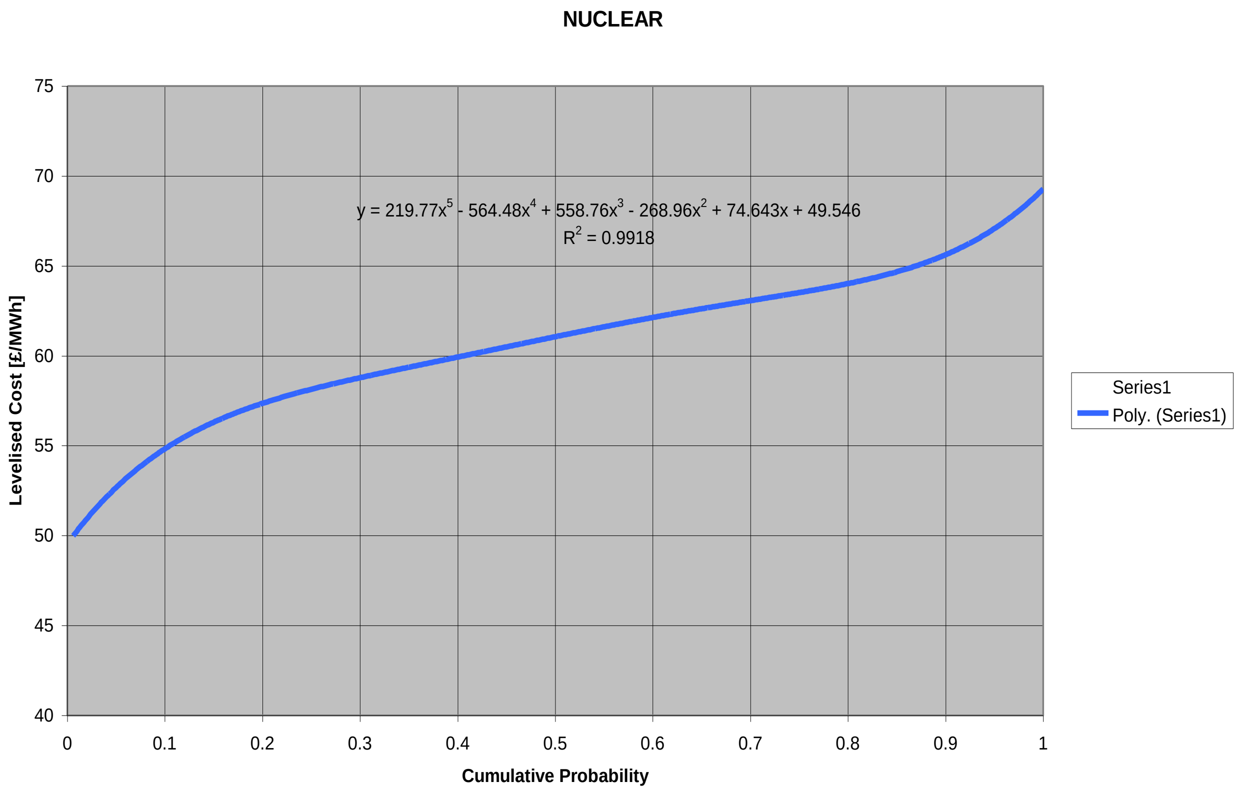
Low	82%	20% probability
Central	85%	60% probability
High	87.5%	20% probability

5.4 Results of the Probabilistic Study of Nuclear

5.4.1 The results are contained within the Nclr Worksheet.

5.4.2 The median value of the trendline is £61/MWh, and the central 80% of probable outcomes covers the range £55 - 66/MWh.

5.4.3The resultant 'S – curve' is shown below.



6. Severn Tidal Barrage

6.1 The Basic Study for the Severn Tidal Barrage

6.1.1 The basic case utilises data from a MacAlpine report of 2002 for the DTI – ETSU Report No. T/09/00212/00/REP. The scheme studied is for a **Capacity** of 8640MW with an **Annual Output** of 17TWh.

6.1.2 The value of **Flood Control** is recognised in the DTI report as being a significant offset to the levelised cost, but the possible range given is so large as to be meaningless on its own. The range given for year 0 is £40-200m p.a., and could increase to well over £4000m p.a. within the life of the station. This first study, in an endeavour to make it meaningful, uses a fairly modest credit of the average of the DTI year 0 range i.e. £120m p.a. for the life of the station. The resultant credit is £8/MWh in the levelised cost.

6.1.3 The **Discount Rate** used for this project is critical since the **Station Life** is taken **as** 120 years. This study assumes that the project will be re-financed at the end of the construction period and commencement of the operational period which should be very low risk since none of the plant being utilised is innovative – it is moderately sized, low head turbine generators. The following **Finance** input parameters were used: -

Construction period : (a) A Return on Equity of 12.5% real.
(b) A Cost of Debt of 6.5% real after tax.
(c) Gearing of 50%. This gives a resultant discount rate of 9.5%.

Operational period : (a) A Return on Equity of 12.5% real.
(b) A Cost of Debt of 4% real after tax
(c) Gearing of 90%. It is assumed that these long term bonds will be attractive to investors with long term liabilities e.g. pension funds. This gives a resultant discount rate of 4.85%.
(d) An Investment Rate of 5% real was assumed for the fund to make any payments at the end of the operating life.
This is higher than for other types of generation projects since it is low risk and has a long life and, therefore equity investment is considered appropriate.

6.1.4 The DTI paper gives a **Capital Cost** of £14bn at 2001 prices for the 8640MW scheme. This study uses £18bn (corrected at RPI for 2010 prices). The **Incidence of Expenditure** is assumed to start in year –5 and extend into year +1 as follows : -

Year	-5	-4	-3	-2	-1	0	+1
% spend	10	15	20	20	15	10	10

6.1.5 The **Plant Availability** is assumed to be 95%. This is not unreasonable for low head hydro plant. The **Energy Output** is assumed to increase from 20% in year 0 by 20% p.a. to reach full output by year 4.

6.1.6 The central figure for levelised **Operating Costs** is taken from the DTI report as £4/MWh at 2001 prices. The RPI corrected figure to 2010 prices used is £5.2/MWh.

6.1.7 Because of the high power output, there will be extra **Transmission Costs** compared to more distributed generation. Informal discussions with National Grid indicate these to be about £1bn, giving a contribution to levelised cost of £3/MWh.

6.1.8 Because of the timing and range of the tides, limited storage, and allowing for plant availability, the project will be limited in the contribution it makes to meeting system peak demand to about 20% of installed capacity on average. Thermal plant will, on average contribute 87.5%. The difference is assumed to be met by OCGTs used as **Back-up**. The capital charges of this plant have been charged to the barrage project. The OCGTs will require to be refurbished perhaps every 30 years. Because of the low load factor that will be required for back-up duty, only 15% of the initial capital has been charged to the barrage project for refurbishment. Similarly, the fuel cost has been ignored.

6.1.9 An A**ncillary Services** credit of £7/MWh has been allowed for frequency control.

6.1.10 The basic study gave a levelised cost of £76/MWh.

6.2 Sensitivity of the Basic Study for the Severn Barrage

6.2.1 The sensitivity of the output parameter of levelised cost was tested for 10% variations in the various input parameters with the following results : -

	Levelised Cost	% Variation on £76/MWh
Capital Cost	83	+9
Cost of Debt (construction)	76	0
Cost of Debt (operation)	83	+9
Equity Return	80	+5
Flood Credit	76	0
Energy output	70	+8
Gearing (operations)	89	+17

6.2.2 From this, Gearing (operations), Capital Cost, Cost of Debt (operations), and Energy Output were taken as the key variables.

6.3 The Probabilistic Study for the Severn Barrage

6.3.1 There is little or no data on probabilities for the various ranges of input parameters that are being considered. Therefore, probabilities have simply been assigned on the basis of 'engineering judgement. [This would be a useful area for further study.]

6.3.2 The range of values for the **Gearing (operations)** was taken as +/- 5 percentage points, but with the probabilities skewed to the lower value as follows : -

Low	85% gearing	25% probability
Central	90% gearing	65% probability
High	95% gearing	10% probability

6.3.3 The range of **Capital Cost** considered was taken from the McAlpine report and probabilities assigned as follows : -

Low	£15.3bn	20% probability
Central	£18bn	60% probability
High	£20.7bn	20% probability

6.3.4 For **Cost of Debt (operations)** a range of +/- 0.5 percentage points was considered with assigned probabilities skewed to the higher level as follows : -

Low	3.5%	20% probability
Central	4%	50% probability
High	4.5%	30% probability

6.3.5 A range of **Energy Output** of +/- 5% was considered. This takes account of variations in both tidal energy available and plant availability. Probabilities were assigned as follows : -

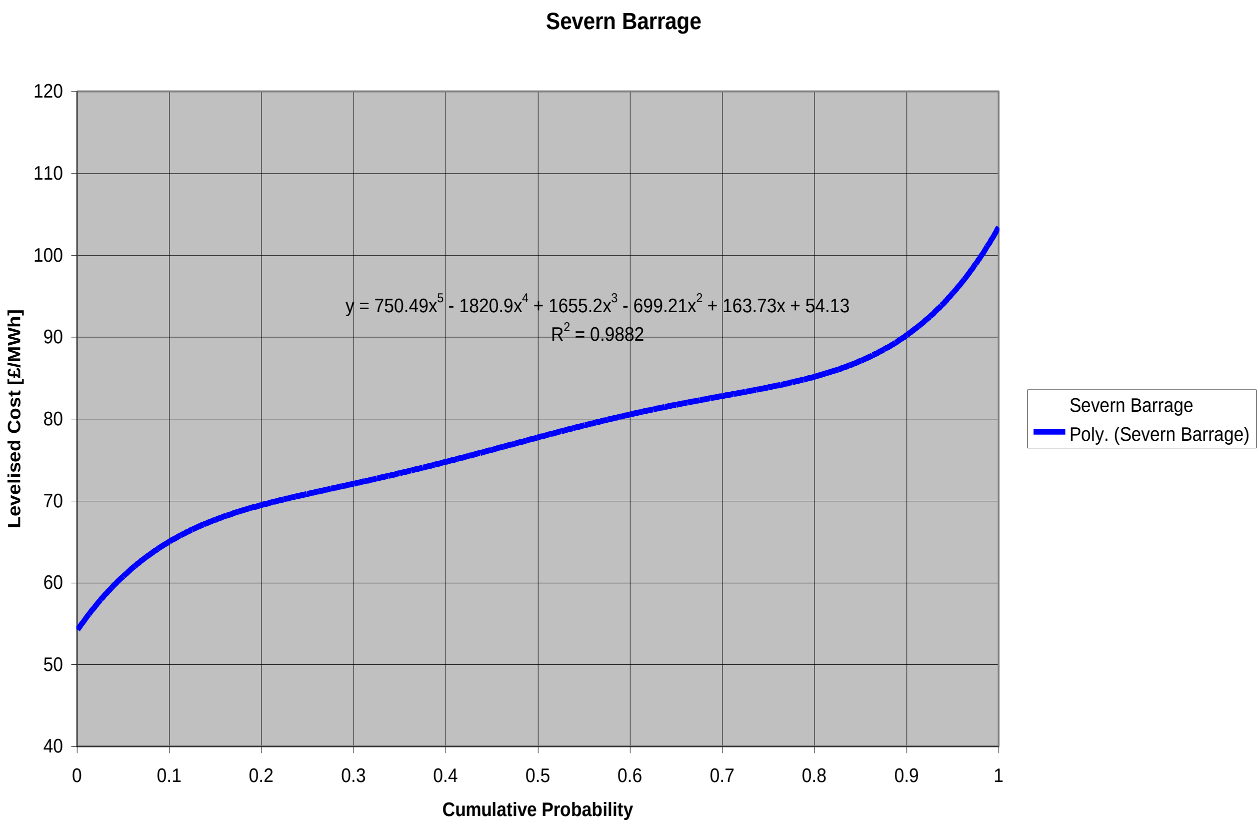
Low	16.15 TWh	15% probability
Central	17 TWh	70% probability
High	17.85 TWh	15% probability

6.4 Results of the Probabilistic Study of the Severn Barrage

6.4.1 The results are contained within Sevrn Woksheet.

6.4.2 The median value of the trendline is £78/MWh, and the central 80% of probable outcomes covers the range £64-90/MWh.

6.4.3The resultant ‘S – curve’ is shown below.

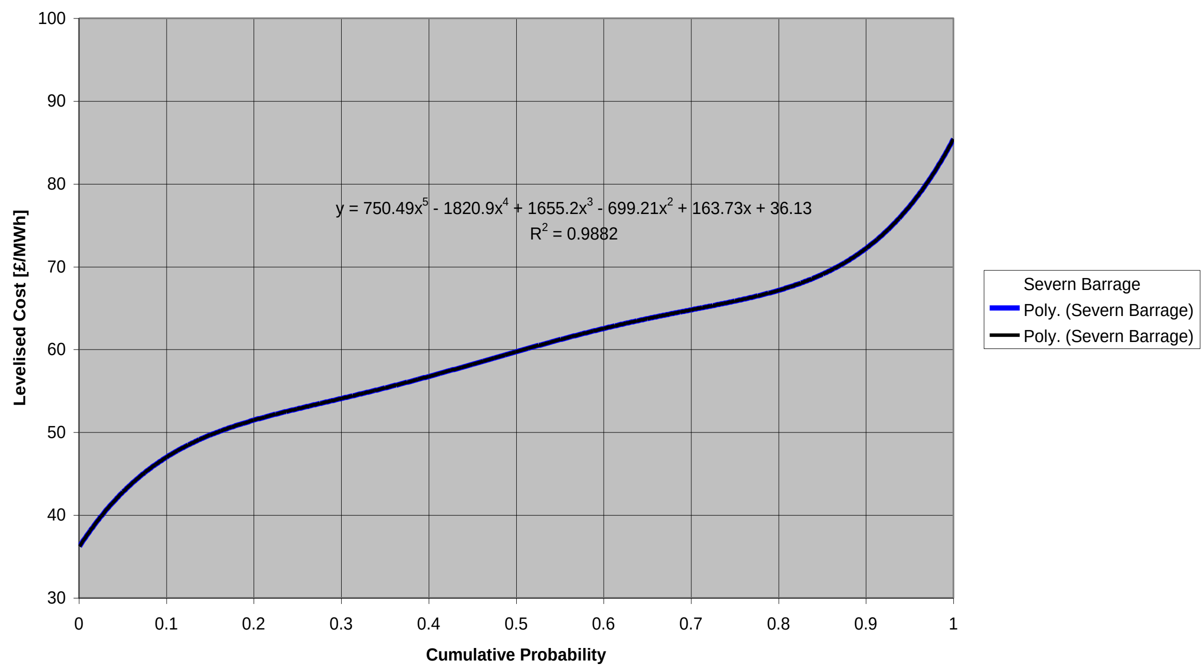


6.4.3 The above study takes a rather pessimistic view of the values of flood credits in that the £120m p.a. is based on 2001 prices. At 2010 prices this would be £160m p.a. Taking this as the Year 0 credit and escalating it at approximately 3% p.a. would give a figure of £4000m p.a. (the maximum in the McAlpine paper) in Year 119.

6.4.4 The spreadsheet has the facility to specify both the credit in Year 0 and the rate of escalation.

6.4.5 Using these higher values of credit for flood control gives the following result.

Severn Barrage 2



7. Combined Cycle Gas Turbine (No carbon capture)

7.1 The Basic Study for CCGT

7.1.1 The basic model used the following **Finance** input parameters : -

(a) A Return on Equity of 12.5% real.
(b) A Cost of Debt of 4.5% real after tax.
(c) Gearing of 50%. This gives a resultant discount rate of 8.5%.
(d) An Investment Rate of 2.5% real was assumed for the fund to make any payments at the end of the operating life.

7.1.2 This study uses **Capital Costs** of £718/kW from the Mott MacDonald/DECC paper for a NOAK. So, for a **Capacity** of 830MW the cost is £595m. The **Incidence of Expenditure** is taken to be:

Year -4	5%
Year -3	5%
Year -2	45%
Year -1	45%

7.1.3 **Auxiliary Power** is taken as 2.3% giving 811MW sent out, and a **Gross Efficiency** of 59%.

7.1.4 A **Station Life** of 30 years and an **Availability** of 91% are assumed.

7.1.5 The central figure for **Operating Costs** of £29.8m/year (including insurance, excluding transmission) was taken from the Mott MacDonald /DECC study.

7.1.6 The Mott MacDonald report uses **Fuel Costs** supplied by DECC and takes the average of these over the period 2015 to 2030. This study uses a different approach: it takes the average central forecast cost for these 15 years of 68 p/therm as the cost in year 0 then escalates this at 3% p.a. [Is this too high? An exponential trendline drawn through gas prices (RPI corrected) since 1996 would indicate a price of about 58p/therm and current actual price is about 40p/therm.]

7.1.7 The basic study gave a levelised cost of £75/MWh

7.2 Sensitivity of the Basic Study for CCGT

7.2.1 The sensitivity of the output parameter of levelised cost was tested for 10% variations in the various input parameters with the following results : -

	Levelised Cost	% Variation on £60/MWh
Capital Cost	76	+1
Return on Equity	75	0
Cost of debt	75	0
Gearing	75	0
Load Factor	74	-1
Operating costs	76	+1
Year 0 Fuel Cost	81	+8
Fuel Cost Escalator	77	+3
Station Life	76	+1
Station Efficiency	70	-7

7.2.2 All the sensitive inputs are related to fuel cost. The input variables were taken as Year 0 Fuel Cost, Fuel Cost Escalator, and Station Efficiency.

7.3 The Probabilistic Study for CCGT

7.3.1 The **Year 0 Fuel Cost** range was taken from the Mott MacDonald / DECC on the same basis as the basic study: this gives a range of 38 to 90 p/therm. The probabilities were assigned to take account of the issues as expressed in 7.1.6 above: -

Low	38p/therm	Probability 40%
Central	68p/therm	Probability 50%
High	90p/therm	Probability 10%

[If there were sufficient data available it would be better to input, perhaps, five values for Year 0 Fuel Cost.]

7.3.2 The Mott MacDonald paper gives a range of **Station Efficiencies** of +/- 1 percentage point about the central figure of 59%. With no data available, probabilities were simply assigned as follows : -

Low	58%	Probability 30%
Central	59%	Probability 40%
High	60%	Probability 30%

7.3.3 The **Fuel Cost Escalator** was varied by –2 and +4 percentage point about 3% p.a. but the probabilities were skewed towards the lower value to allow for the possibility of shale gas having a containing effect on gas prices. This results in the following : -

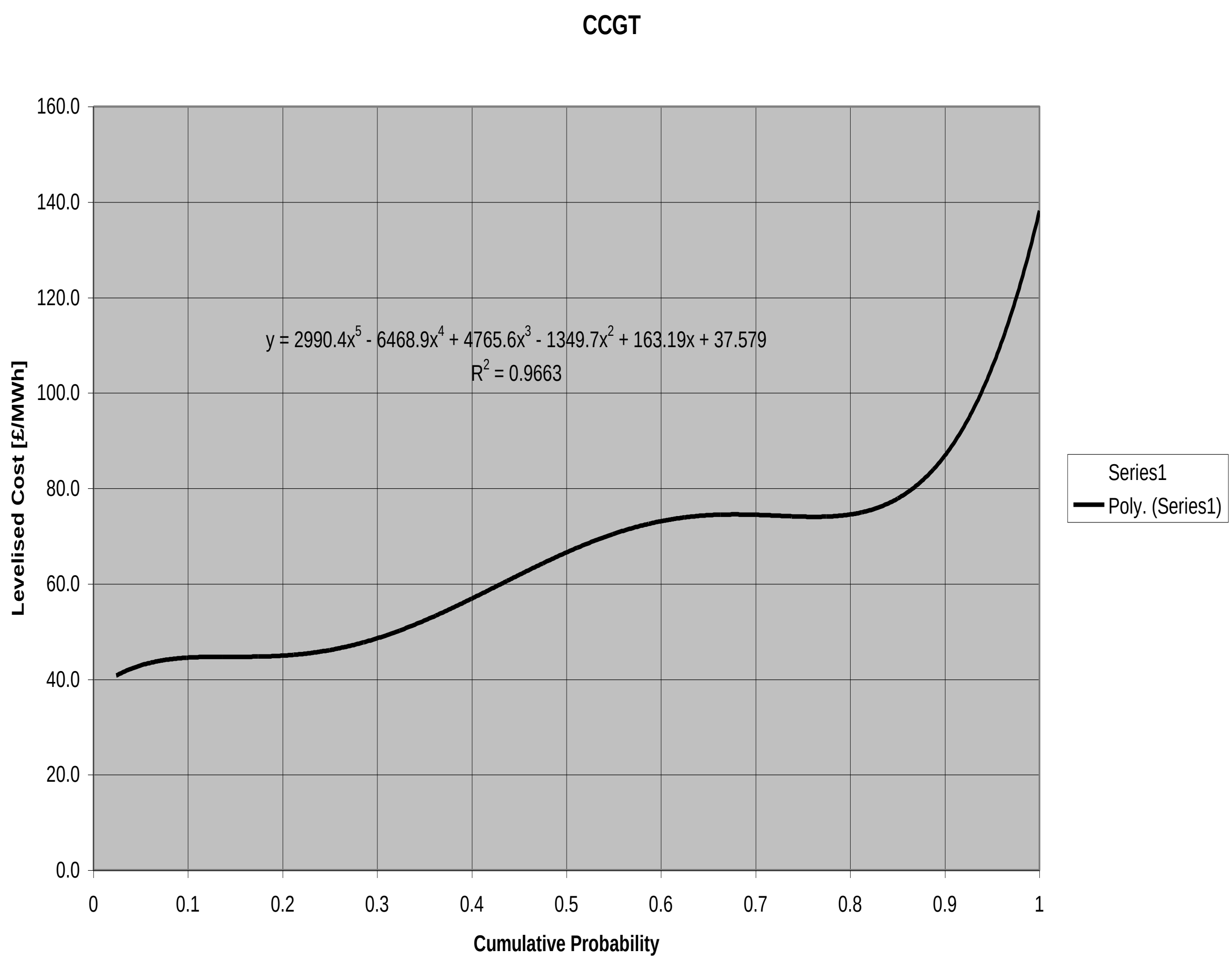
Low	1%	Probability 30%
Central	3%	Probability 60%
High	7%	Probability 10%

7.4 Results of the Probabilistic Study of CCGT

7.4.1 The results are contained within Gas Worksheet.

7.4.2 The median value of the trendline is £66/MWh, and the central 80% of probable outcomes covers the range £45 - 88/MWh.

7.4.3 The resultant 'S – curve' is shown below.



8. Coal1 (No carbon capture)

8.1 The Basic Study for Coal

8.1.1 The basic model used the following **Finance** input parameters : -

(a) A Return on Equity of 12.5% real.
(b) A Cost of Debt of 4.5% real after tax.
(c) Gearing of 50%. This gives a resultant discount rate of 8.5%.
(d) An Investment Rate of 2.5% real was assumed for the fund to make any payments at the end of the operating life.

8.1.2 This study uses **Capital Costs** from the Mott MacDonald/DECC paper for a NOAK of £1768/kW. So, for a **Capacity** of 1600MW the cost is £2828m. The **Incidence of Expenditure** is taken to be :

Year –7	5%
Year –6	5%
Year –5	5%
Year -4	5%
Year -3	10%
Year -2	35%
Year -1	35%

8.1.3 **Auxiliary Power** is taken as 6.5% giving 1496MW sent out, and a **Gross Efficiency** of 45%.

8.1.4 A **Station Life** of 40 years and an **Availability** of 90.2% are assumed.

8.1.5 The central figure for **Operating Costs** of £102.8m/year (including insurance, excluding transmission) was taken from the Mott MacDonald /DECC study.

8.1.6 The Mott MacDonald report uses **Fuel Costs** supplied by DECC and takes the average of these over the period 2015 to 2030. This study uses a different approach: it takes the average central forecast cost for these 15 years of $80/t as the cost in Year 0 then escalates this at 3% p.a. The Year 0 Cost is equivalent to 20p/therm or £17.3/MWh s.o.

8.1.7 The basic study gave a levelised cost of £60/MWh

8.2 Sensitivity of the Basic Study for Coal

8.2.1 The sensitivity of the output parameter of levelised cost was tested for 10% variations in the various input parameters with the following results : -

	Levelised Cost	% Variation on £60/MWh
Capital Cost	63	+5
Return on Equity	62	+3
Cost of debt	61	+2
Gearing	59	-2
Load Factor	57	-5
Operating costs	61	+2

Year 0 Fuel Cost	62	+3
Fuel Cost Escalator	61	+2
Station Life	60	0
Station Efficiency	58	-3

8.2.2 The two most sensitive inputs are Capital Cost and Load Factor (availability), but Equity Return, Year 0 Fuel Cost and Station Efficiency (both of which affect Cost of Energy sent out) are moderately sensitive. Equity Return was taken a third independent variable, and Year 0 Fuel Cost and Station Efficiency were combined into one input variable.

8.3 The Probabilistic Study for CCGT

8.3.1 The range of **Capital Costs** was taken from the Mott MacDonald/DECC report (less infrastructure) as £1768/kW for the central case, with a low case of £1560/kW and a high case of £1964/kW. No probabilities are given so these were simply assigned as follows : -

Low £1560/kW	Probability 20%
Central £1768/kW	Probability 60%
High £1964/kW	Probability 20%

8.3.2 The range of **Load Factors** was taken from the Mott MacDonald / DECC paper and probabilities were assigned as follows: -

Low	88.2%	Probability 20%
Central	90.2%	Probability 60%
High	91.2%	Probability 20%

8.3.3 The central figure for **Equity Return** of 12.5% was taken from the Citigroup nuclear paper, and returns of a low of 11.5% to a high of 13.5% were assumed. Probabilities were assigned as follows : -

Low	11.5%	Probability 20%
Central	12.5%	Probability 60%
High	13.5%	Probability 20%

[This is an area where more data is required.]

8.3.4 The Mott MacDonald/DECC paper gives the range of **Fuel Costs** as : -

Low	$50/t	12.5p/therm
Central	$80/t	20p/therm
High	$100/t	25p/therm

It also gives a range of **Gross Efficiencies** of +/- 1 percentage point about 45%. Using this to extend the range of **Year 0 Fuel Costs** gives the following (probabilities have simply been assigned) :-

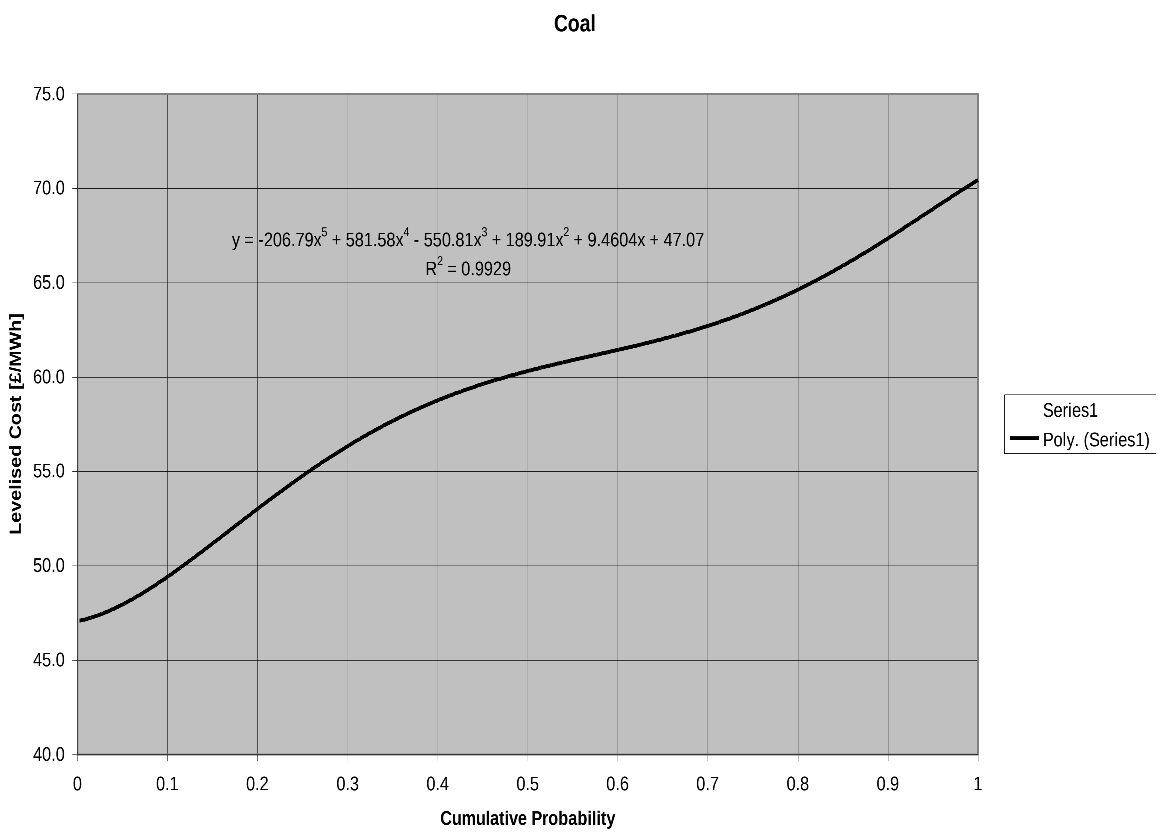
Low	12.2p/therm	Probability 25%
Central	20p/therm	Probability 50%
High	25.55p/therm	Probability 25%

8.4 Results of the Probabilistic Study of Coal without CCS

8.4.1 The results are contained within Coal1 Woksheet.

8.4.2 The median value of the trendline is £60/MWh, and the central 80% of probable outcomes covers the range £49 - 67/MWh.

8.4.3 The resultant 'S – curve' is shown below.



9. Coal2 – Advanced Supercritical with CCS

9.1 The Basic Study for Coal - Advanced Supercritical with CCS

9.1.1 The basic model used the following **Finance** input parameters : -

(a) A Return on Equity of 12.5% real.
(b) A Cost of Debt of 4.5% real after tax.
(c) Gearing of 50%. This gives a resultant discount rate of 8.5%.
(d) An Investment Rate of 2.5% real was assumed for the fund to make any payments at the end of the operating life.

9.1.2 This study uses **Capital Costs** from the Mott MacDonald/DECC paper for a NOAK of £2412.5/kW. So, for a **Capacity** of 1600MW the cost is £3860m. The **Incidence of Expenditure** is taken to be:

Year – 8	5%
Year –7	5%
Year –6	5%
Year –5	5%
Year -4	5%
Year -3	10%
Year -2	30%
Year -1	35%

9.1.3 **Auxiliary Power** is taken as 15.5% giving 1352MW sent out, and a **Gross Efficiency** of 36%.

9.1.4 A **Station Life** of 38 years and an **Availability** of 89% are assumed.

9.1.5 The central figure for **Operating Costs** of £151m/year (including insurance, excluding transmission) was taken from the Mott MacDonald /DECC study.

9.1.6 The Mott MacDonald report uses **Fuel Costs** supplied by DECC and takes the average of these over the period 2015 to 2030. This study uses a different approach: it takes the average central forecast cost for these 15 years of $80/t as the cost in Year 0 then escalates this at 3% p.a. The Year 0 Cost is equivalent to 20p/therm or £21.7/MWh s.o.

8.1.7 The basic study gave a levelised cost of £88/MWh

9.2 Sensitivity of the Basic Study for Coal

9.2.1 The key input parameters were taken to be the same as Coal (without CCS) which are CAPEX, Load Factor, Equity Return, and Year 0 Fuel Cost

9.3 The Probabilistic Study for Coal ASC with CCS

9.3.1 The range of **Capital Costs** was taken from the Mott MacDonald/DECC report (less infrastructure) as £2412.5/kW for the central case, with a low case of £2205/kW and a high case of £2620/kW. No probabilities are given so these were simply assigned as follows : -

Low £2205/kW	Probability 20%
Central £2412.5/kW	Probability 60%
High £2620/kW	Probability 20%

9.3.2 The range of **Load Factors** was taken from the Mott MacDonald / DECC paper and probabilities were assigned as follows: -

Low	84.5%	Probability 20%
Central	89%	Probability 60%
High	90.6%	Probability 20%

9.3.3 The central figure for **Equity Return** of 12.5% was taken from the Citigroup nuclear paper, and returns of a low of 11.5% to a high of 13.5% were assumed. Probabilities were assigned as follows : -

Low	11.5%	Probability 20%
Central	12.5%	Probability 60%
High	13.5%	Probability 20%

[This is an area where more data is required.]

9.3.4 The Mott MacDonald/DECC paper gives the range of **Fuel Costs** as : -

Low	$50/t	12.5p/therm
Central	$80/t	20p/therm
High	$100/t	25p/therm

It also gives a range of **Gross Efficiencies** of +/- 1 percentage point about 36%. Using this to extend the range of **Year 0 Fuel Costs** gives the following (probabilities have simply been assigned) :-

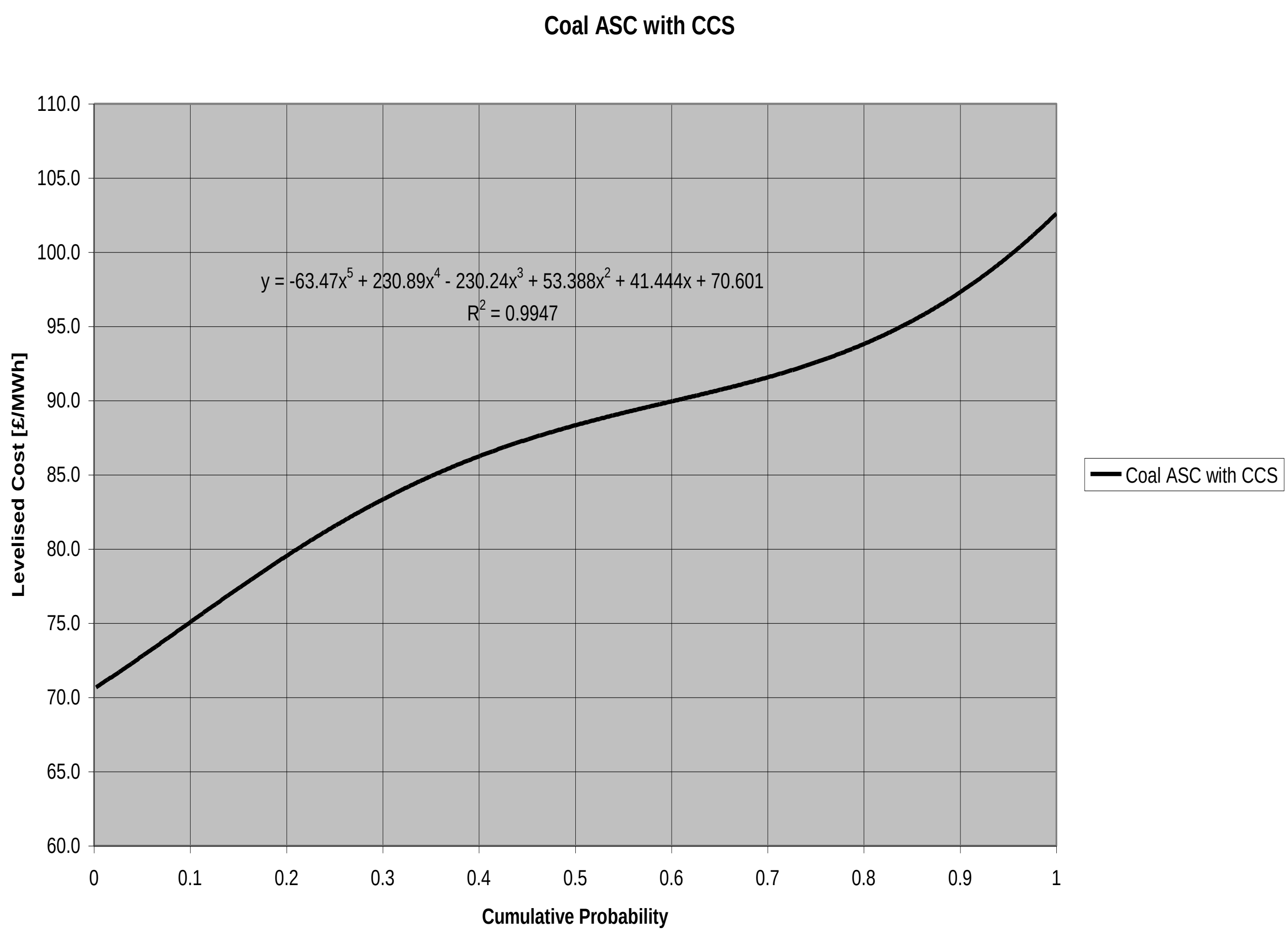
Low	12.2p/therm	Probability 25%
Central	20p/therm	Probability 50%
High	25.55p/therm	Probability 25%

9.4 Results of the Probabilistic Study of Coal – ASC with CCS

9.4.1 The results are contained within ………………………….

9.4.2 The median value of the trendline is £88/MWh, and the central 80% of probable outcomes covers the range £75-97/MWh.

9.4.3 The resultant 'S – curve' is shown below.



10. Coal3 – Integrated Gasification Combined Cycle with CCS

10.1 The Basic Study for Coal - Integrated Gasification Combined Cycle with CCS

10.1.1 The basic model used the following **Finance** input parameters : -

(a) A Return on Equity of 12.5% real.
(b) A Cost of Debt of 4.5% real after tax.
(c) Gearing of 50%. This gives a resultant discount rate of 8.5%.
(d) An Investment Rate of 2.5% real was assumed for the fund to make any payments at the end of the operating life.

10.1.2 This study uses **Capital Costs** from the Mott MacDonald/DECC paper for a NOAK of £2403/kW. So, for a **Capacity** of 870MW the cost is £2090m. The **Incidence of Expenditure** is taken to be:

Year –8	5%
Year –7	5%
Year –6	5%
Year –5	5%
Year -4	5%
Year -3	5%
Year -2	35%
Year -1	35%

10.1.3 **Auxiliary Power** is taken as 13.5% giving 753MW sent out, and a **Gross Efficiency** of 36%.

10.1.4 A **Station Life** of 30 years and an **Availability** of 87.4% are assumed.

10.1.5 The central figure for **Operating Costs** of £74.9m/year (including insurance, excluding transmission) was taken from the Mott MacDonald /DECC study.

10.1.6 The Mott MacDonald report uses **Fuel Costs** supplied by DECC and takes the average of these over the period 2015 to 2030. This study uses a different approach: it takes the average central forecast cost for these 15 years of $80/t as the cost in Year 0 then escalates this at 3% p.a. The Year 0 Cost is equivalent to 20p/therm or £21.7/MWh s.o.

10.1.7 The basic study gave a levelised cost of £102/MWh

10.2 Sensitivity of the Basic Study for Coal

10.2.1 The key input parameters were taken to be the same as Coal (without CCS) which are CAPEX, Load Factor, Equity Return, and Year 0 Fuel Cost

10.3 The Probabilistic Study for CCGT

10.3.1 The range of **Capital Costs** was taken from the Mott MacDonald/DECC report (less infrastructure) as £2403/kW for the central case, with a low case of £2195/kW and a high case of £2610/kW. No probabilities are given so these were simply assigned as follows: -

Low £2195/kW	Probability 20%
Central £2403/kW	Probability 60%
High £2610/kW	Probability 20%

10.3.2 The range of **Load Factors** was taken from the Mott MacDonald / DECC paper and probabilities were assigned as follows: -

Low	84.1%	Probability 20%
Central	87.4%	Probability 60%
High	89.9%	Probability 20%

10.3.3 The central figure for **Equity Return** of 12.5% was taken from the Citigroup nuclear paper, and returns of a low of 11.5% to a high of 13.5% were assumed. Probabilities were assigned as follows : -

Low	11.5%	Probability 20%
Central	12.5%	Probability 60%
High	13.5%	Probability 20%

[This is an area where more data is required.]

10.3.4 The Mott MacDonald/DECC paper gives the range of **Fuel Costs** as : -

Low	\$50/t	12.5p/therm
Central	\$80/t	20p/therm
High	\$100/t	25p/therm

It also gives a range of **Gross Efficiencies** of +/- 1 percentage point about 36%. Using this to extend the range of **Year 0 Fuel Costs** gives the following (probabilities have simply been assigned): -

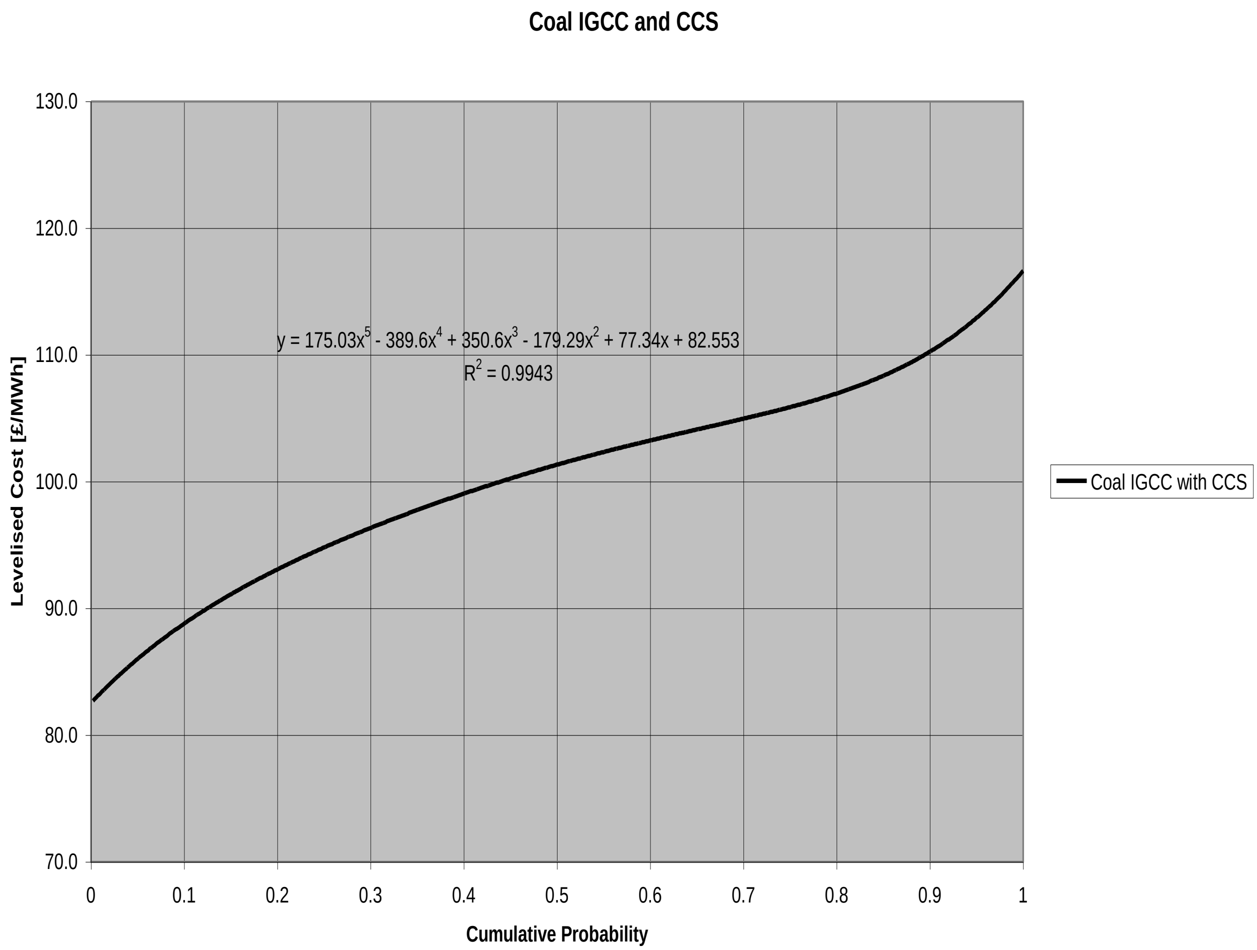
Low	12.2p/therm	Probability 25%
Central	20p/therm	Probability 50%
High	25.55p/therm	Probability 25%

10.4 Results of the Probabilistic Study of Coal

10.4.1 The results are contained within …………………

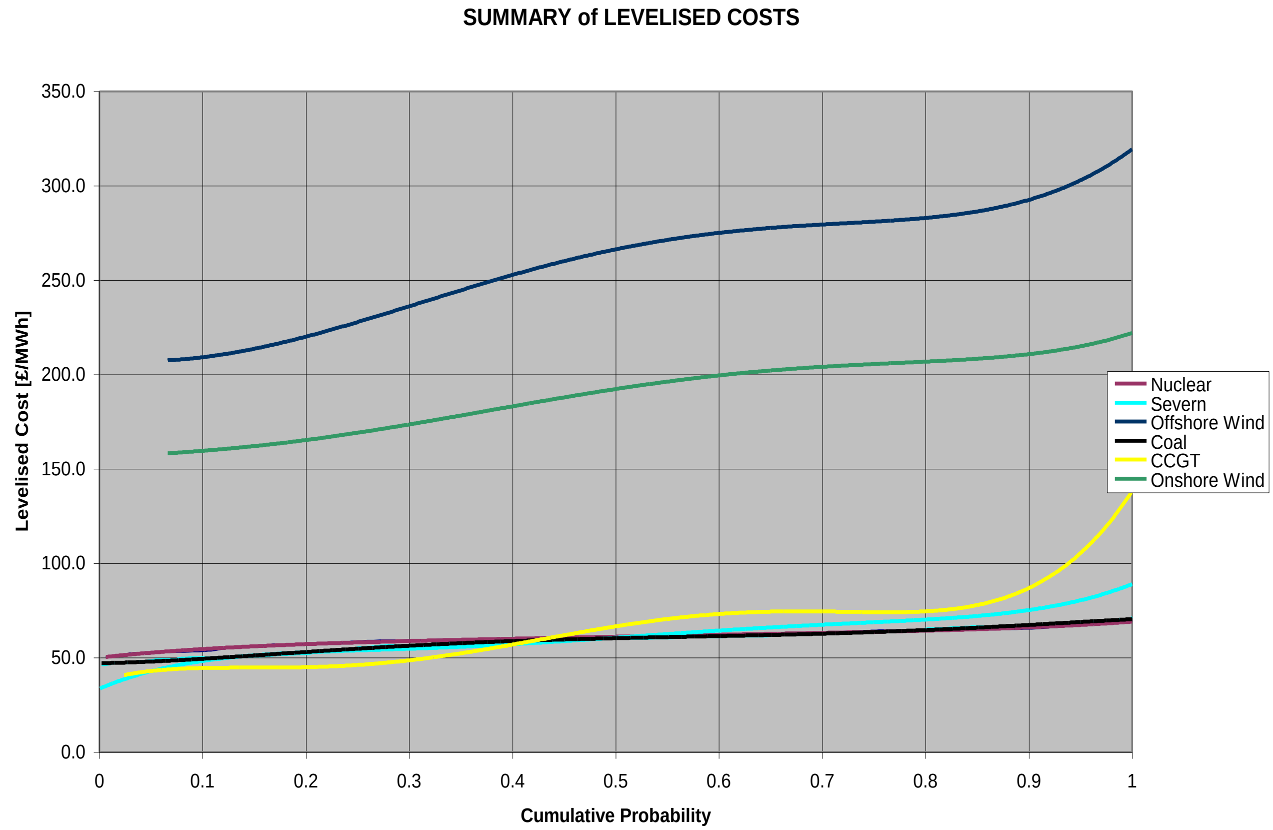
10.4.2 The median value of the trendline is £102/MWh, and the central 80% of probable outcomes covers the range £89- 110/MWh.

10.4.3 The resultant 'S – curve' is shown below.



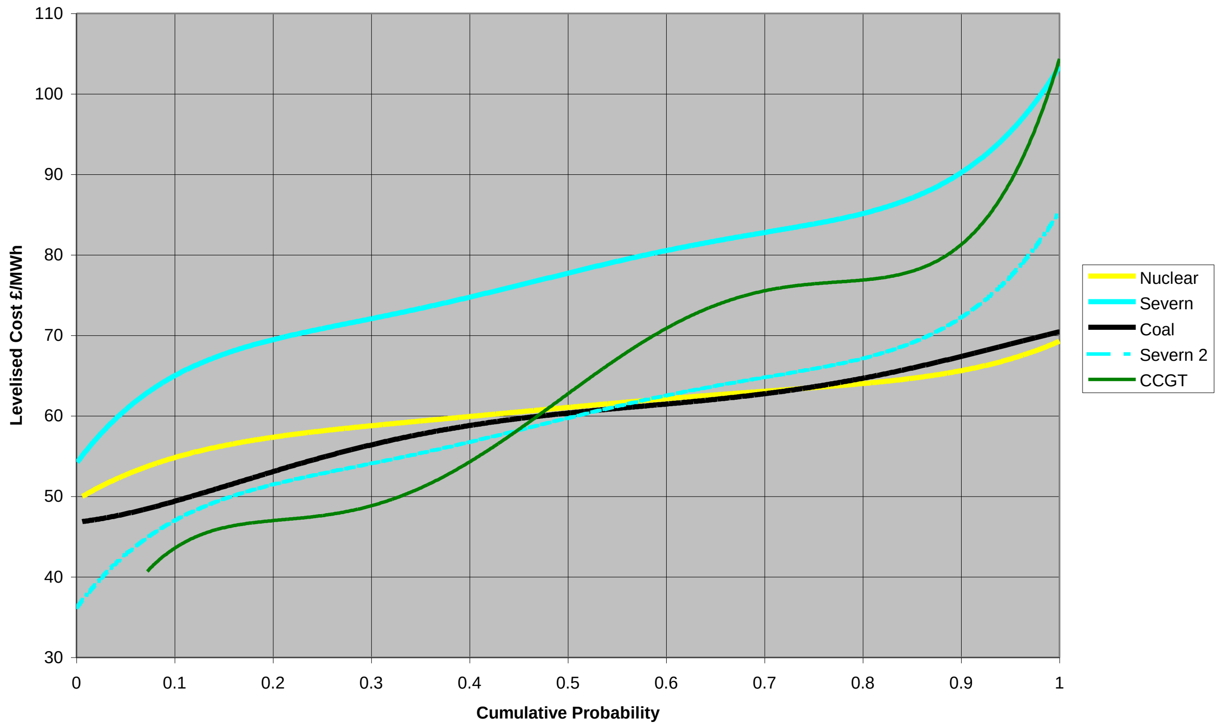
11. Conclusions (Interim)

11.1 The ‘S-Curves’ for all the types of generation considered are shown on the summary chart below.



11.2 This clearly shows the levelised costs for nuclear, the Severn Barrage, CCGTs, and coal being grouped together in the range broadly £50 – 100/MWh. However, wind generation costs are significantly higher: on-shore being in the range £150 – 220/MWh; off-shore being in the range £200 – 320/MWh.

11.3 In order to show more clearly the differences between the non-wind generation types, the graph below shows these costs on a summary chart with a false zero.



11.4 This shows nuclear and coal to have a very similar range of levelised cost, broadly £50- 70/MWh, and to have very similar uncertainty (slope of the curve).

11.5 The CCGT curve demonstrates the considerable uncertainty caused by the uncertainty of fuel costs. The costs are in the range £40-105/MWh.

9.6 The Severn Barrage with a range of £55-105/MWh is higher than other non-wind generation, but it should be remembered that only a single, rather moderate value was taken for the value of flood control. This main study was done with the flood control credit at 2001 prices (the MacAlpine study). Correcting the £120pa used to 2010 prices would give a figure of £160pa. This was used in Severn Barrage 2, and was escalated to give a credit of £4000pa by year 120 (the figure from the MacAlpine study for within the life of the station. This showed a reduction of £18/MWh over the main study range. On this basis, the Severn Barrage with a range of levelised cost of broadly £35-85/MWh is similar to nuclear and coal but with greater uncertainty.

Appendix Validation analysis for the levelised cost estimates

Basic definition of levelised cost

1.1 The levelised cost is a discounted average cost per unit of energy over an investment period.

1.2

The levelised cost of energy - LEC is calculated using Expression (1):

$$LEC = \frac{\sum_{i=1}^{n} \frac{I_t + M_t + etc}{(1+r)^t}}{\sum_{i=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (1)$$

where:

n is the number of years of the investment period
t is one of the years during period n
I_t is the cost of the investment in year t
M_t is the cost of operation and maintenance in year t

etc represent costs from other sources in year t e.g. fuel cost, cost of backup generation
E_t is the number of Megawatt hours generated by the facility during year t
r is the discount rate

That is for each year of the investment period the cost are calculated and discounted. The sum of the costs for all years is then established. This is divided by the sum of the energy generated over the *n* years also discounted to present value. The discounting of the energy takes account of the change in value of the energy over the period.

1.2 The following process was used to calculate the cost probabilities:

1. A selection of the input variables were chosen as being dominant. These are the *key variables*.
2. For each of the key variables. values representing low, central and high estimates were defined and corresponding probabilities assigned to them.
3. The number of combinations *N* of variables and probability is:

$N = n_p^v$
where n_p is the number of probabilities per key variable and v is the number of key variables.
For example with 4 key variables and 3 probabilities per variable $N = 3^4 = 81$

4. The levelised cost for each combination is calculated
5. Each of the combinations is associated with v probabilities. Say with 4 key variables there would be four probabilities p_1, p_2, p_3, p_4 The combined probability p_v for a combination of key variable values is calculated as: $p_v = p_1 \times p_2 \times p_3 \times p_4$
6. The N values of levelised cost and corresponding p_v probabilities are set up in an ordered list from lowest to highest cost.
7. The cumulative probability for each item in the ordered list is calculated as the sum of the probabilities for all the costs less than and equal to the item.
8. Levelised cost against cumulative probability is then plotted.

General validity of the levelised cost model

There are many limitations to the use of Equation (1). It is a useful approximate method of comparing the costs of different types of generation assuming that the generation can be run at its maximum possible load factor i.e. it is not constrained by the load curve or the running of other plant. A more thorough method of comparing types of generation and plant mix is to run total system cost studies for various combinations of plants.

The individual cost items (I_t M_t *etc*)

It is most important that the all contributory costs are included when using Equation (1). As noted in Section 3, the DTI and Parsons Brinkerhoff estimates do not appear to include all cost items in their final figures, although the existence of these costs is recognised in the text. There is some confidence that the C Gibson estimates do include all the main costs but there is much uncertainty about the values used for the cost items. The values used were gathered from a number of sources. There is a degree of commercial confidentiality regarding these costs

The discount factor

Table 2 indicates the sensitivity of the cost of offshore wind and nuclear generation to the value of the discount factor.

Table 2 Sensitivity of discount rate for cost of offshore wind and nuclear

Discount rate - r %	Cost £/MWhr		% increase from r = 8%	
	Offshore wind	Nuclear	Offshore wind	Nuclear
8	238	58	0	0
9	250	63	5	9
10	262	69	10	19
11	274	75	14	29
12	287	82	21	41

The effect of the discount rate is more significant with nuclear because of the higher investment costs.

Validity of the probability approach

A significant amount of judgement was used to establish the values of probability and in choosing the key variables used. In principle, accuracy of prediction could be improved by increasing the numbers of key variables and probabilities but, in view of the shortage of data for establishing the values of the data variables and the probabilities, such refinement may not achieve better outcomes.

Overall Assessment

Because of the limitations of the levelised cost approach and uncertainty about the data, the cost predictions presented here will tend to give only broad indication of trends rather than accurate predictions. The important feature of the model is that an attempt has been made to include all the factors that affect the cost of generation.