CITY UNIVERSITY LONDON

COMPARING THE RISKS OF DIVERSE METHODS OF ELECTRICITY GENERATION USING THE J-VALUE FRAMEWORK

by

JAMES KEARNS

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Part 2 Comparative Risk Analysis of Electricity Generating Systems in the United Kingdom

The intention of the second part of this thesis is to evaluate and compare risks to human life posed by electricity generating systems within the UK. This is done by using the J-value framework to evaluate the loss of life expectancy from a variety of sources of risk, as described in part 1. In addition to this, financial risks resulting from large accidents causing environmental damage will also be evaluated using the J_2-value approach described in chapter 10, although the main focus of the work will be regarding human risks. The chosen technologies for analysis are nuclear, coal, natural gas, onshore wind and offshore wind, which together currently generate over 90% of the UK's electricity, and will likely continue to do so in the near future, for example, see DECC (2011d) [51]. A complete fuel-chain approach has been taken, in which impacts involved with all stages from extraction to waste disposal are considered.

This is the first research to evaluate risks from such systems using the J-value method to monetise the risks. Monetisation is achieved by calculating the theoretical cost that would be required in order to eliminate all risks presented by electricity generating systems that would give $J = 1$. This quantity is the "hazard elimination premium" (HEP), which was introduced in chapter 7, where the usefulness of this quantity in risk comparison was discussed. This cost can be interpreted as the additional burden on human health resulting from the generation of electricity. This cost is then the "external cost of risk", a term more commonly used in the literature, see, for example ExternE (1995) [77]. For financial risks, the maximum reasonable cost of eliminating that risk can be calculated directly. This is simply the quantity, δZ_R, of equation (10.7). Other new contributions made in this thesis include the use the most recent statistics available, and a more complete analysis of the impacts of the construction materials. In particular, occupational fatality statistics specific to each energy technology can now be obtained. This is important for renewable technologies, where there has historically been little data available.

A review of existing literature in the field of comparative risk analysis of energy systems is given in chapter 12. Chapter 13 then gives an overview of the risk analysis, describing the scope, system boundaries, calculations used and data quality issues. Chapter 14 presents the impacts associated with acquisition and transportation of construction materials, which are common to all electricity generating systems. In chapters 15, 16 and 17, the impacts associated with nuclear, fossil and wind electricity generation respectively. The comparative analysis is presented in chapter 18, and the results are then discussed in chapter 19.

Chapter 12 Literature Review

The practice of comparing risks quantitatively is a relatively recent phenomenon. It arose in the mid-seventies in response to, and as a means to address public concern with complex technologies that were imposing unfamiliar hazards on both humans and the environment. Research into the psychology of risk had demonstrated that perceptions of risk by non-experts were frequently at odds with the true magnitude of the risk. In particular, risks that were familiar tended to be underestimated, whilst unfamiliar risks were usually overestimated, see Lichtenstein et al (1978) [130]. Comparative risk analysis was therefore put forward as a tool that could aid in informing the public of the nature of the new hazards posed by an expanding industrial sector, the rationale being that such comparisons give risks a context and provide a frame of reference that is more intuitive and more meaningful to the user than absolute values considered in isolation.

The literature on comparative risk analyses can be divided into two categories, as is done by Covello (1991) [43]. These are: comparisons of diverse sources of risk, and comparisons of similar sources of risk. The former typically uses measures such as the annual death rate, or collective loss of life expectancy as a common unit of risk, and compares a wide variety of hazardous activities and causes of death. One of the earliest major studies of this kind was by Cohen and Lee (1979) [37], who produced a “Risk Catalogue”, which used loss of life expectancy to compare a somewhat eclectic collection of risks. Some of the greatest risks calculated in this study were of remaining unmarried, smoking, heart disease and being a coal miner, whilst the least hazardous activities were from the operation of nuclear power plants. Another early major study of this type was by Crouch and Wilson (1982) [46], who calculated the required time for which exposure to the risk would increase the probability of death by one in one million. The activities which required the least amount of time according to this measure were: fire fighting, coal mining, railroad employment and police duty.

The second type of risk analysis compares similar sources of risk. These types of studies are useful when faced with a choice of which technology or activity to implement or prioritise. Whilst the first type of study is useful for providing risks in context, and therefore aids the judgement of the acceptability of any new risk, the second type of study informs the public and decision makers about the likely prospects of different courses of action. The analyses of comparative risks from energy and electricity production technologies are of this second type. One of the earliest studies of this type was by Lave and Freeburg (1973) [128], which compared health effects of electricity generation by coal, oil and nuclear fuel. The Atomic Energy Commission (1974) [14] compared fossil fuels with nuclear and hydroelectric power. Comar and Sagan (1976) [38] also published studies that compared the risks from nuclear power to fossil fuels, whilst Caputo (1977) [28] published one of the earliest studies comparing non-conventional electricity generating technologies to conventional fossil fuel technologies. This study compared orbital solar power plants that transmit solar power to earth by microwave with ground based solar plants and conventional nuclear and fossil plants. The most widely known comparative risk assessment of energy technologies of this period was the study by Inhaber (1978a) [109] on behalf of the Atomic Energy Control Board of Canada, summaries of which were also published in various journals and magazines see Inhaber (1978b) [110], and (1979) [111]. This report used “risk accounting” – a method of evaluating all sources of risk at each stage of the energy production chain (what would now be known as life-cycle analysis) to compare the total risk of eleven different energy technologies, including coal, oil, natural gas, nuclear, wind, hydroelectricity, ocean thermal, methanol and three types of solar technologies. The study was the most systematic and rigorous of all the risk comparison literature of the period. Nevertheless, the conclusions of the report – that non-conventional energy technologies were not inherently low risk – provoked furious criticism (see, e.g. Holdren (1979) [97]). The final revision of the report, as well as most of the critical comments, were published in a subsequent book, see Inhaber (1982) [112].

The early 1980s saw the first publications of comparative risk analyses of energy and electricity production in Britain. Cohen and Pritchard (1980) [35] produced a report for the Health and Safety Executive that reviewed the literature on the comparative risks of coal, oil and nuclear energy. Much of the data used in the study applied to environments outside of the UK, but nevertheless bore some relevance to the UK. The measures of risk used in this study were accidental deaths, accidental injuries, pneumoconiosis deaths, and cancer deaths, all of which were evaluated per unit of electricity generated. The plants studied were assumed to have a capacity of one gigawatt, and operated at 75% of this capacity. The authors of this report emphasised the importance of studying whole systems, and partitioned their data into the following fuel chain stages:

- Fuel extraction, processing and fabrication
- Power plant operation

The authors also reviewed some selected major accident risks, which were compared with some major risks from non-fossil or nuclear energy systems in an attempt to provide some context.

This was followed a similar report published by Ferguson(1989)[83], on behalf of the Newcastle Energy Centre, which also studied coil, oil and nuclear technologies. The nuclear power plant was assumed to be an advanced gas-cooled reactor (AGR). The risk measures used were occupational and public accidents and disease, evaluated, again, per unit of electricity generated. The fuel chain stages were partitioned more finely than in the Cohen and Pritchard study, with the following stages being analysed:

- Fuel extraction
- Preparation and transport
- Electricity generation

The author of the study warned that the results of the study must be considered in accompaniment with some caveats, which were of the uncertain nature of the estimated risks from pollution and radiation.

Although the previous two studies were the most important pieces research in the field of comparative risk analyses of UK energy systems during this period, there were some other publications that helped to advance the field. Cohen (1983) [36] published a follow up paper that examined the conceptual foundations of such analyses, and identified many potential pitfalls present in both producing and interpreting the results of such analyses, as well as issues involved with conveying results to a wider audience. Pochin (1977) [162] also published a short paper comparing risks from coal, oil, nuclear, natural gas and hydroelectricity, using figures largely based on previous research. Fremlin (1987) [85] gave an excellent account of the issues of risk involved in power production, comparing coal, oil, natural gas, nuclear, hydroelectricity, wave and wind energy. Fremlin also included an estimate of the risks from a mediaeval water mill for comparison, and interestingly, also includes an estimate of the risk from energy conservation, noting that improved insulation will cause greater exposures to pollution and radiation.

Increasing concerns about the environment and energy security brought the need for renewable technologies more sharply into focus. In 1989 Fritzsche produced an analysis of risks from a series of electricity technologies thought to be generally applicable to Europe [86]. The various technologies were split into three groups. The first group was fossil fuels, and included coal, oil, natural gas and wood. The second group was renewable energy systems, which included solar technologies, wind and hydroelectric. The third group was nuclear technologies. Risks were delineated according to whether they were occupational risks or public risks, and whether they were acute risks or delayed risks. Severe accidents were also treated separately. Risks were presented in terms of fatalities per GWa over all stages of the fuel chain. The conclusions were that the highest risks were from severe accidents of coal, oil, gas and hydroelectric, and from public delayed risks resulting from coal and oil. Renewables generally presented medium to low risks, whilst nuclear technologies presented low risks.

Ball et al (1994) [15] published the first in-depth analysis of the risks of proposed renewable energy technologies in the UK, and compared them with nuclear and fossil fuels. Plant capacities for non-renewable technologies were taken as one gigawatt, and the nuclear plant was assumed to a pressurised water reactor (PWR). The renewable technologies studied were tidal, onshore wind and offshore wind. The risk measures used by the study were number of acute occupational fatalities, chronic risks of occupational disease, and delayed fatality risks to the public, all of which are estimated per unit of electricity generated. The study also analysed whole fuel chains, and the data was delineated according to the following fuel chain stages:

- Fuel Extraction
- Fuel Preparation/Reprocessing
- Materials/Component Fabrication
- Plant Construction
- Power Plant Operation
- Transport
- Decommissioning
- Waste Disposal

This study also separately analysed the health impacts from pollution and major accidents, emphasising the large uncertainties inherent in the process. The authors note that defining system boundaries is essential if the analysis is to be consistent, and if the comparisons are to be meaningful. It is for this reason that risks from acquiring construction materials were included in the fuel chain, as these are major sources of risk for renewable technologies. The authors also note, however, that truncating the analysis at some point is necessary, as the system is in practice limitless. For example, the risks of acquiring materials used to construct the mine used to acquire the materials used in constructing the power plant is part of the energy system, although most people would judge this risk as being sufficiently far removed from the energy generating process that it can be neglected. Such a truncation would always be arbitrary, and its suitability is dependent upon the judgement of the authors. In this report, a risk level of less than 0.1 fatalities or serious health detriments per gigawatt-year (GWa) is used as a guide of where risks become less significant.

The mid-1990s saw the publication of the first reports of the ExternE project (1995) [77]. The ExternE (External Costs of Energy) project is a research program of the European Commission, comprised of more than 50 research teams in 20 countries. The project, which began in 1991 and is still ongoing, aims to evaluate on a monetary basis all human and environmental damages caused by energy production systems. These damages are known as "external costs", because their impact is usually not reflected in the price of the energy. The project has been very rigorous and systematic in the damages it has analysed and evaluated. The initial publications compared the marginal impacts (impacts caused by building an extra power plant) of coal, lignite, oil, gas, nuclear, wind and hydroelectric energy systems, with a particular focus on the impacts in the UK and Germany. The fuel chain stages used in the project are much the same as listed above, but also include transmission of electricity to a grid (although this impact is very small). However, there was not a single standard fuel chain used for all energy technologies, with each technology being assessed on a fuel chain that was judged to be most relevant to that particular technology. This approach means comparisons of energy technologies at stages of the fuel chain are not used. Instead, comparisons are between risk measures, such as occupational health and disease, evaluated over the whole fuel chain. For human health risks, the impacts assessed include occupational and public fatalities, injuries and diseases. Other costs assessed include amenity impacts (e.g. visual intrusion) and ecological impacts (e.g. earth movements, acid emissions and greenhouse gas emissions). Each impact is evaluated in terms of monetary cost per unit of electricity generation. Contingent Valuation methods were used for valuing mortality and morbidity reductions. The project uses a Value of Temporarily Preventing a Fatality of €2.6M. Since the initial publications in 1995, the ExternE project has expanded its scope, including assessments of impacts in other European countries, including the new EU countries in Central and Eastern Europe. Emerging energy technologies have also been analysed, see ExternE (1999) [78], (2004) [79], (2005) [80] and (2008a) [81]. The later publications also assessed other impacts, and improved some aspects of the methodology, such as changing the valuation of air pollution impacts from number of premature fatalities to years of life lost, and including the effects from chronic exposure to pollution, rather than just acute effects, as had been the case in earlier publications. New methods of valuing impacts were also considered, such as inferring the external cost of eco-system damages from political negotiations.

Table 16 summarises the main features of the major studies of comparative risks of UK energy generating systems.

Study	Risk Measures	Fuel Chains Considered	Fuel Chain Stages Assessed	Monetary Evaluation?
Cohen and Pritchard, 1980, [35]	Accidental deaths, accidental injuries, pneumoconiosis deaths, cancer deaths. All normalised per GWa	Coal, oil, nuclear	- Fuel extraction, processing and fabrication - Power plant operation	No
Ferguson, 1981, [82]	Occupational accidents, occupational disease, public accidents, public disease. All normalised per GWa	Coal, oil, nuclear AGR	- Fuel extraction - Preparation and transport - Electricity Generation	No
Fritzsche, 1989, [86]	Acute occupational and public fatalities, delayed occupational and public fatalities. Fatalities from severe accidents. All normalised per GWa	Coal, oil, natural gas, wood, solar – thermal, solar photovoltaic, wind, hydroelectric, nuclear LWR, nuclear HTR, nuclear FBR, nuclear fusion	Not specified	No
Ball et al, 1994, [15]	Acute occupational fatalities, chronic occupational disease, public delayed fatalities. All normalised per GWa	Tidal, onshore wind, offshore wind, nuclear PWR, coal, oil, gas	- Fuel extraction - Preparation/ reprocessing - Materials/ component fabrication - Plant construction - Power plant operation - Transport - Decommiss-ioning - Waste Disposal	No
ExternE, 1995, [77]	Public health, occupational health – diseases, occupational health – accidents.	Coal, lignite, oil, gas, nuclear PWR, onshore wind, hydroelectricity	No standard fuel chain, but similar to above. Also includes electricity	Yes – uses Contingent Valuation approach, with VTPF of €2.6M

	Note these are just health impacts. Study also estimates other environmental impacts. All normalised per TWh		transmission as a stage	
ExternE, 1999, [78], 2004, [79], 2005, [80], 2008, [81].	As above	As above, but also includes biomass, offshore wind photovoltaic, solar thermal, wave, tidal	As above	Yes – VTPF lowered to €1.0M (2004), and used VOLY of €50k for pollution mortality

Table 16 Summary of literature on UK comparative risk analyses.

Chapter 13 Overview of the Analysis

13.1 Scope of the Report

As discussed in the introduction to part two, risks will be evaluated for five different technologies: nuclear, coal, gas, onshore wind and offshore wind. These five technologies together account for over 90% of all electricity generated in the UK as of 2009, see DECC (2011d) [51], (gas – 43%, coal – 27%, nuclear – 19%, onshore wind – 2%, offshore wind 0.5%). These technologies are chosen as they are assumed to be representative of the UK electricity mix, both now, and in the future. The risks are assessed over a time period of 60 years, from 2010 to 2070. It is assumed that other current technologies, such as oil and hydroelectricity, emerging technologies, such as solar, tidal and biomass, and those still in development, such as nuclear fusion, will not contribute significantly to the generation of electricity within the UK over this time period.

The impacts considered are human mortality risks presented over the whole of the fuel chain, as it is now recognised that any planning of electricity generation should, where possible, account for all health damages, as indirect impacts can often be a major contributor to the full social cost of the electricity supply, see e.g. IAEA (1999) [107]. In addition, financial risks associated with major accidents have also been assessed. The following fuel chain has been used where appropriate to the source of generation:

- Extraction
- Preparation and fabrication
- Generation
- Reprocessing
- Waste Disposal
- Transport

This fuel chain accounts for the primary fuel used in the generation of electricity. Each of these processes may be divided into three further sub-processes: construction, operation and decommissioning, although not all these stages will require assessment in every case. It is also necessary to define a separate chain that accounts for the materials used in construction of the associated facilities. This materials chain is similar to that shown above, except that there is no generation or reprocessing stage. Furthermore, not all construction materials will be eventually disposed of, as materials such as steel will be recycled. The full fuel/material chains are shown in Figure 28.

The mortality risks are separated into occupational and public risks, and immediate and delayed fatality risks, with the latter being due to exposures from radiation, pollution (arising from emissions of particulate matter) and dust (which may cause pneumoconioses). Risks are also categorised as due to normal or abnormal operation, the latter referring to major accidents, where societal concerns may be particularly acute.

The dependence of the impacts upon the scale of growth of each technology over the period 2010 to 2070 has also been assessed. This allows impacts to be assessed on three scales: current risks, future risks and incremental risks. Current risks describe the present value of the impacts arising from the existing stock of power plants currently generating electricity over the assessed period, including all decommissioning that may take place. Future risks are those arising from both the current stock of power plants and the new build plants, where a given scale of construction can be specified. Future risks are therefore always greater than the current risks. The impacts of both current and future risks are normalised against the amount of electricity generated over this period. For example, if the present value of all risks arising from the current stock is R_1, and the amount of electricity generated is O_1, then current impacts are R_1/O_1. If the future risks are $R_2 = R_1 + \Delta R$, where ΔR is the additional risk resulting from the new build, and the new amount of electricity generated is $O_2 = O_1 + \Delta O$, where ΔO is the additional electricity generated over the period, then the future impacts are R_2/O_2. The incremental risk is then $\Delta R/\Delta O$, that is, the additional risks resulting from new build only. These three situations are shown in Figure 29. Knowledge of any two of these risks allows the third to be calculated. Here, consideration will be given to current and incremental risks. The incremental risks will also form the main focus of the comparative analysis and the conclusions.

There are a number of important impacts which lie outside the scope of this report. Of these, the major impacts are: morbidity risks, such as injuries and non-fatal diseases; impacts associated with greenhouse gases and global warming; and security risks, such as those presented by terrorism.

13.2 System Boundaries

In order that meaningful comparisons can be made, it is necessary to define in a clear and consistent manner, exactly what should be included and excluded from such an analysis – i.e. what exactly constitutes a "system". The systems under examination in this report – those of electricity generation, are by their nature very complex, both affecting and being affected by a large number of factors. This means there are no distinct boundaries by which to delineate the system, and consequently, any such definition of system boundaries must be arbitrary. This arbitrariness makes it essential that the boundaries are clearly specified, and that a high level of consistency is maintained throughout the analysis. These boundaries are:

- The time boundary:
  - The majority of impacts considered occur between 2010 and 2070.
  - The only exception is public radiation does from nuclear plants, where the available data used cumulative doses truncated after 500 years.
- The space boundary:
  - Only transportation of materials within the UK is assessed.
  - Immediate public fatalities (the majority of which arise from transportation accidents) are assessed for the UK population only.
  - Delayed public fatalities arising from pollution are assessed for the European population, as particulate matter emitted from UK stations cannot travel over distances larger than this.

- Delayed public fatalities resulting from radiation are assessed over three regions: UK, Europe and the world. These regions are used to assess sensitivities as is described in section 13.4.
- Occupational impacts are assessed at the location of impact.

- The resource boundary:
  - All stages that involve the generating fuel, from extraction to disposal, including transportation, are assessed. Risks presented over the lifetime of the facility, from construction to decommissioning, provided they occur within the time boundary, are included.
  - Impacts involved in the construction materials chain, from extraction of the raw materials, to waste disposal or recycling, and again including transportation, are included.
  - Impacts outside these two chains (e.g. construction of the facility at which the material is fabricated) are excluded.

In addition to these boundaries, it is also necessary to add some caveats. It was assumed that present technologies will be used in the future. Clearly, technological change can lead to improvements in efficiencies and availabilities. Such changes would however, be impossible to predict. Assuming a constant technology for each type of electricity generation therefore is the best means of comparison.

Similarly, it is also assumed that risks per unit of electricity generated remain constant over the timeframe of the study. This assumption is also unrealistic as most industries have experienced a trend of improving safety levels, which is likely to remain the case in the future. Predicting such changes would be impossible, and so this has not been attempted for any technology. As far as is possible, risks have been estimated from data for the most recent five-years, from 2006 to 2010.

It has also been assumed that each technology is supplying baseload energy. This means they produce electricity continuously in order to meet some or all of the UK's continuous electricity demand. This contrasts with other modes of electricity generation, such as peaking plants, which deal with sudden surges in demand.

Another caveat is that all life expectancy calculations are determined from UK statistics. Clearly, a more realistic calculation would use statistics appropriate to the region concerned. However, this assumption will give conservative results, in that they overestimate the effects, rather than underestimate them. The largest overestimation will be for nuclear power, in which some uranium mining statistics were based on Namibian data, where the life expectancy is lower than in the UK. Also, if the world region was used for the collective dose estimation, then mortality statistics for the global population should be used, which would result in lower impacts than are calculated here. Pollution impacts would not be affected greatly, as European mortality statistics are generally similar to the UK.

13.3 Calculation of Impacts

To compare the impacts from different electricity generation methods, it is necessary to use the Hazard Elimination Premium, or HEP, which is a metric developed in chapter seven. It was discussed that this metric is important for risk comparisons as it provides a valuation of the benefit obtained from eliminating the risk posed by each system. The first stage of determining the impacts is to calculate the loss of life expectancy posed by a risk. This is done by assuming that all sources of risk contribute an additional burden upon the average mortality rates currently experienced by the population, as are given in the national interim life tables, see ONS (2009a) [145]. For sources of risk that are to be added to the system over the time period, this will be the case. However, for existing sources of risk this is slightly unrealistic, as the national mortality rates already include any fatalities that occurred in the fuel chain (within the UK). This means that the true impact would need to be estimated by comparing the current mortality rates with those that would exist if the fuel chain impacts were deleted from the national statistics. This approach has not been pursued here, which can be justified because such impacts represent a very small proportion of the national mortality rates, and so can be treated as if they were independent of them.

To calculate the loss of life expectancy, the additional hazard rate must first be estimated, using the methods described in section 5.4, see equation (5.7). In the context of power generation, impacts are either immediate fatalities, for example resulting from falls or vehicle accidents where death occurs almost immediately, or delayed fatalities, which arise from exposures to pollution and radiation, and which result in latent effects so that death does not occur until some years later. To calculate the effects of immediate fatalities, it is necessary to estimate the annual exposure rate, *b* (which is assumed constant over time), which is simply the average annual number of deaths *D*, divided by the average number of people exposed to the risk. Where possible, these averages will be performed over the most recent five years. This period is judged to be long enough to capture any natural variation in the fatality rates, but also short enough so as to exclude data that may not be relevant to the current situation. The five year period is also favoured by the ExternE series, see ExternE (1995) [77].

For delayed fatalities, knowledge is required of the radiation doses to workers and the emissions of radiation and particulate matter (specifically, PM2.5) into the environment, which then cause public health effects. Once these are ascertained, the increase in hazard rate and the loss of life expectancy can be readily determined using the methods described in section 5.9. There are also impacts due to occupational exposures to dust from coal mining and quarrying. However, the life expectancy from these impacts is calculated from national mortality statistics, rather than through estimation of the exposure rate and the consequent probability of death. The current mortality statistics from these illnesses arise from exposures that occurred a few decades ago. In order to estimate the effects of current exposures, the present loss of life expectancy is extrapolated forward towards a point in time where the mean age of death of coal worker's pneumoconiosis sufferers is equal to mean age of the present workforce, which will be about 40 years from now. This method, was originally used by Ferguson [83], and is described in more detail in Appendix C.

One result that is useful for assessing the public impacts of radiation and pollution is that the change in life expectancy is directly proportional to the exposure rate, *b*, i.e. that:

$$\delta X \propto b \quad (13.1)$$

as can be seen from equation (8.28). The quantity δX is the individual loss of life expectancy. In the J-value framework, this quantity is then multiplied by the average number of exposed individuals, N. The product $N\delta X$ may then be viewed as the collective loss of life expectancy δX_{coll}. This can be expressed as:

$$N\delta X = \delta X_{coll} \propto b_{coll} \tag{13.2}$$

where b_{coll} is the collective hazard rate. This formulation is useful for assessing public exposures, where data is frequently presented in terms of the collective dose received. In such cases, the collective impact can be assessed without needing to estimate N, which simplifies the estimation procedure. However, as collective doses are commonly in excess of 100 mSv, care must be used to avoid inadvertently applying the DDREF factor, see equation (5.46). This can be avoided by dividing the collective dose by a factor of, say 1,000 or 10,000 so that the dose is below the 100 mSv threshold, calculating the loss of life expectancy, and multiplying back by that same factor. The collective loss of life expectancy can then be monetised to give the HEP. As described in chapter 7, this is the maximum reasonable cost of eliminating all risk posed by the source, such that $J = 1$, so that, from equation (3.61):

$$\delta \hat{V}_N = \delta V_N = \frac{GN\delta X}{1-\varepsilon} \frac{\left(1 - e^{-r_d X_d}\right)}{r_d X_d} \tag{13.3}$$

where the values of the parameters are given by Table 6.

In order to provide calculations that are normalised against the unit of energy generated, a slightly different approach may be taken. As will be discussed later, the approach taken in this report is to compare risks from each technology at all levels of aggregated data – from comparisons of the hazard rates at each fuel chain stage, where the data is completely disaggregated, to comparisons of the total risk for each energy technology, which is the highest level of data aggregation. In order that the comparisons at each stage are meaningful, it is necessary to use appropriate normalisations at each stage. This can be done by defining a new hazard rate. Whereas previously the additional hazard rate has been defined *per person*, it is also possible to define an additional hazard rate *per gigawatt-year* (GWa). If the average electrical output of the system over the period when the D deaths occurred is $\langle O \rangle$, then the new additional exposure rate, b^*, for immediate fatalities, is:

$$b^* = \frac{D}{\langle O \rangle} \qquad (13.4)$$

Using this exposure rate allows an additional hazard rate, δh^*, and loss of life expectancy per GWa, δX^*, to be calculated. If the system will give an output of O gigawatt-years over the period under assessment, then the collective change in life expectancy is $O\,\delta X^*$, and the HEP is:

$$\delta V_N^* = \frac{GO\delta X^*}{1-\varepsilon} \frac{\left(1 - e^{-r_d X_d}\right)}{r_d X_d} \qquad (13.5)$$

As the *per person* and the *per gigawatt-year* HEP's are approximately independent of either the number of exposed people or the output generated, then the two measures will be approximately equal. This has the great benefit of not needing to estimate the number of people exposed to a risk, which is usually one of the most difficult parameters to assess.

Thus the usual method of calculating individual impacts scaled up by the average number of affected individuals is broadly equivalent with the method of calculating impacts per unit electricity generation, and scaling up by the amount of electricity generated.

The HEP per unit of electricity generated is then:

$$\frac{\delta \hat{V}_N^*}{O} = \frac{G\delta X^*}{(1-\varepsilon)} \qquad (13.6)$$

To calculate the HEP for environmental risks, historical data has been used to estimate the expected number and costs of major accidents. However, for nuclear accidents, data is sparser, and so a probabilistic safety analysis has been used to determine the frequency and cost of large nuclear accidents. This data can then be used to estimate the maximum reasonable cost of eliminating the possibility of large nuclear accident over the lifetime of each power plant. This value is then the HEP for environmental risks to assets.

13.4 Quality of Data

While much of the data used in this research is reliable and known with some certainty, there still remains much data that is either not available or is by its nature highly uncertain. Such uncertainty is accounted for by presenting a range of results. Where possible, the high and low values of the range are determined from 95% confidence limits. When using fatal accident statistics, the 95% limits are calculated using Poisson statistics for cases where fatalities are rare, whereas Gaussian statistics were used for cases where accidents are frequent. In some cases, 95% confidence limits are given in the raw data. When this is not the case, high and low values are taken based on available data, and judgement is used over whether the figures are credible estimates of risk. In addition, when performing the HEP calculations, the high and low values of the input parameters, as shown in Table 6 are used for the respective high and low estimates. Aggregation is performed by taking an appropriately weighted sum of corresponding high or low values. As discussed by Ferguson(1989) [83], the resulting sum will necessarily have a higher confidence level than its parts. A more precise root-mean-square summation could be used, but doing so would not reflect the approximate nature of some of the estimates.

The assumed impacts of radiation exposure also contain some intrinsic uncertainty. Any such exposure is assumed to lead to an increase risk of cancer, with the magnitude of the increase being characterised by a dose-response relationship. Accurate estimation of the true response of these low levels of radiation exposure (typically below what is naturally present as background radiation) is very difficult as such a response, if it exists, is delayed due to the long latency periods required for the cancers to be expressed, and also because any observed increase in cancer incidence is difficult to detect against current levels. Because of these difficulties, it was conservatively assumed that data of the effects of observed high level doses could be extrapolated linearly to low doses. It was also assumed that there was no threshold at which the effect of low level doses ceases to have an effect. Thus, the conventional assumption is that any impinging ionising particle will increase the risk of premature death. This poses issues when considering collective dose, whereby the effects of routine discharges of radionuclides into the atmosphere which become globally circulated can be calculated to have a considerable effect over millions of years, due to billions of individuals receiving extremely low doses. Any such figure would be extremely speculative and should be used with caution. Indeed, the International Commission on Radiological Protection (ICRP) has recently recommended against the use of collective dose in this way, see ICRP (2007) [113]. However, not withstanding this, and the likely pessimistic nature of the conclusions that will be reached by its use without qualification, collective dose has been used in this study as there is no established alternative such as an agreed "threshold dose". However, in order to estimate the likely effect of using collective dose in this way, a range of alternative assumptions on how it might be used have been considered.

In this thesis, public collective doses are determined for three populations: the UK, Europe and the world, which serve as a form of sensitivity analysis providing a range of estimates which entail differing levels of conservatism. The sensitivity of the collective dose impacts to the use of "cut-off" levels is also assessed see e.g. Jones et al (2004) [120]. This involves neglecting all doses to individuals that are below some specified level (the "cut-off" level). For example, Jackson et al (2004) [114] proposed a cut-off dose of 0.01 μSv/a, which results in an individual fatality risk of three orders of magnitude below levels deemed tolerable by the Health and Safety Executive (1992) [98]. Such issues also apply to other delayed impacts due to pollution and dust. It is extremely difficult to assess impacts at low doses, and for many toxins (but not radiation unless a hypothetical cut-off is introduced), a "no observed adverse effects level" is sometimes used, taken to be a threshold below which exposures are safe. However, in order to give better comparability with nuclear radiation, we have not applied such cut-off levels in this study.

The impacts from emissions of toxic substances from coal combustion have not been quantified, due to lack of available data. Arsenic, Cadmium, Chromium and Nickel are all known human carcinogens emitted from coal stations, but their impact on human mortality has not been adequately studied, and so no attempt at quantification has been made here. However, these toxins can become widely circulated, and so the true impact may be substantial.

In order to assess the reliability and robustness of the results, a number of sensitivity studies have been performed, of which many have already been mentioned. These include assessing the effect of calculating radiological impacts over three different regions – the UK, Europe and the world, as well as the effect of introducing cut-off doses. Another issue assessed for sensitivity are the coal mining statistics. This is because UK production of coal is dwindling, and imports are becoming increasingly important, see DECC (2011f) [53]. Much of imported coal comes from Russia and China, where safety levels are different to the UK. The effect of using such safety statistics in place of UK data is therefore also assessed.

13.5 Issues with Aggregation and Presentation of Results

The J-value method uses the loss of life expectancy as a measure of risk. This measure has not been utilised much in the literature, apart from Externe (1999) [78], who use some rudimentary calculations to estimate impacts from air pollution. Nevertheless, the loss of life expectancy represents a much more accurate measure of risk than the more common total number of fatalities. The loss of life expectancy is then monetised to give the HEP. In order that meaningful comparisons can be made, this cost is then normalised against a unit of energy generated. The unit of energy chosen is the gigawatt-year, abbreviated as GWa. There are other ways in which the cost could be normalised, such as per unit capacity, or average cost per person affected, but the method of using the amount of energy generated is now standard practice, see e.g. IAEA (1999) [107], ExternE (2005) [80].

Another important issue is the acceptability of aggregating results from diverse sources of risk. The possibility of using the loss of life expectancy as a unifying "Index of Harm" was considered by Sir Edward Pochin, in two reports for the ICRP see Pochin (1977) [161], (1980) [163]. This was later further expanded on by Hoaksey (1989) [96]. Inhaber used another measure of total risk, namely, the number of working days lost (1982) [112]. This measure has the benefit of being able to assess morbidity impacts such as illness and disease. However, there are a number of drawbacks with this approach, such as difficulties in calculating public and radiological risks. Another measure of total risk is based on monetary cost. The Externe series attempt to calculate all external costs associated with electricity production, see ExternE (1995) [77], (1999) [78], (2004) [79]. The reports present a total external cost for each European nation, normalised against the amount of electricity generated. However, all authors note the dangers of using a single index. Public attitudes are dependent upon the nature of the risk involved, and so a single index has the potential to be misleading. These issues are discussed by Ball et al, (1994) [15], who compare the various dimensions of health risks separately. This position is justified by noting that:

> "The current convention then, is that the health consequences of systems should remain disaggregated, at least into those of immediate fatalities and delayed fatalities, and that there should in addition be a distinction between the two principle groups at risk, the workforce and the public."

However, it is noted here that presenting disaggregated results also have the potential to be misleading. This is because it is not necessarily the case that a technology that is safer than another in each of the disaggregated variables is also safer when the variables are aggregated. This is due a phenomenon known as "Simpson's Paradox", see e.g. Freedman (1998) [84]. The phenomenon arises because comparisons are made on the basis of risk per unit of generated electricity. These quantities are rates, and as such do not obey normal laws of arithmetic. For example, the sum of two rates may not represent any meaningful quantity. These problems have received little consideration from many authors of the previous literature on risk comparison, which may have resulted in an overestimation of the impacts of the larger fuel chains. If rate quantities are aggregated together, then they need to weighted appropriately so as to provide a common basis and hence produce a meaningful sum. The approach taken here has been to weight the HEP's against the total amount of electricity generated by the technology over the period 2010 to 2070. This allows the weighted values to sum in the normal manner.

In this report there will be no preference given to any degree of aggregation, and results will be presented at different levels. At the lowest level of aggregation are the results delineated according to whether they are resulting from normal or abnormal operation, whether they are to the public or occupational, and whether they are immediate or delayed. At the highest level of aggregation is a single figure – the “total risk” from the generating source, although the difficulties with presenting such figures will be noted. This approach therefore assesses the sensitivity of the results on a further dimension, and so adds reliability to any conclusions that may be drawn.

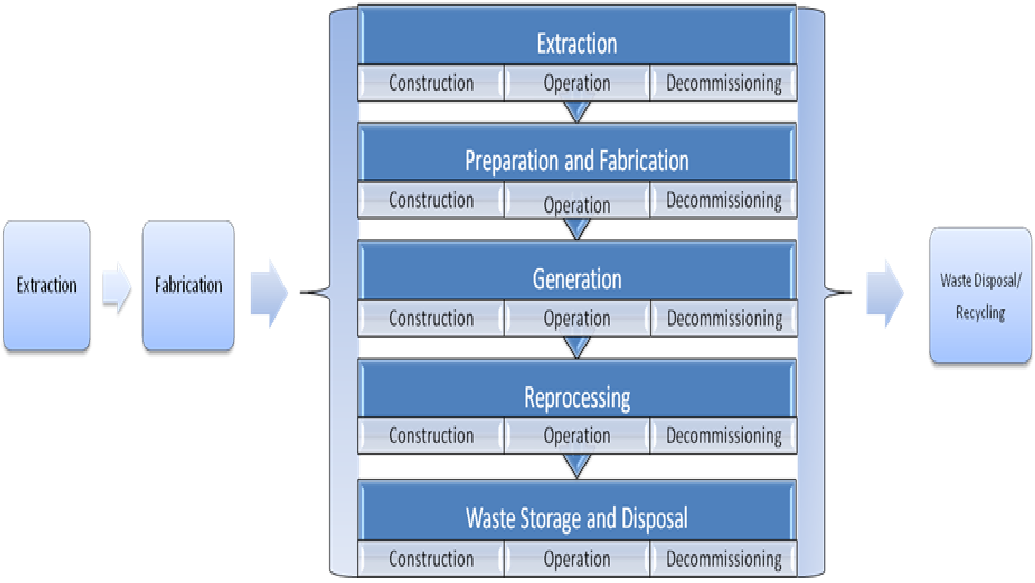

Figure 28 Fuel chain (from top to bottom) and construction materials chain (from left to right) used in the analysis. Arrows indicate transportation processes.

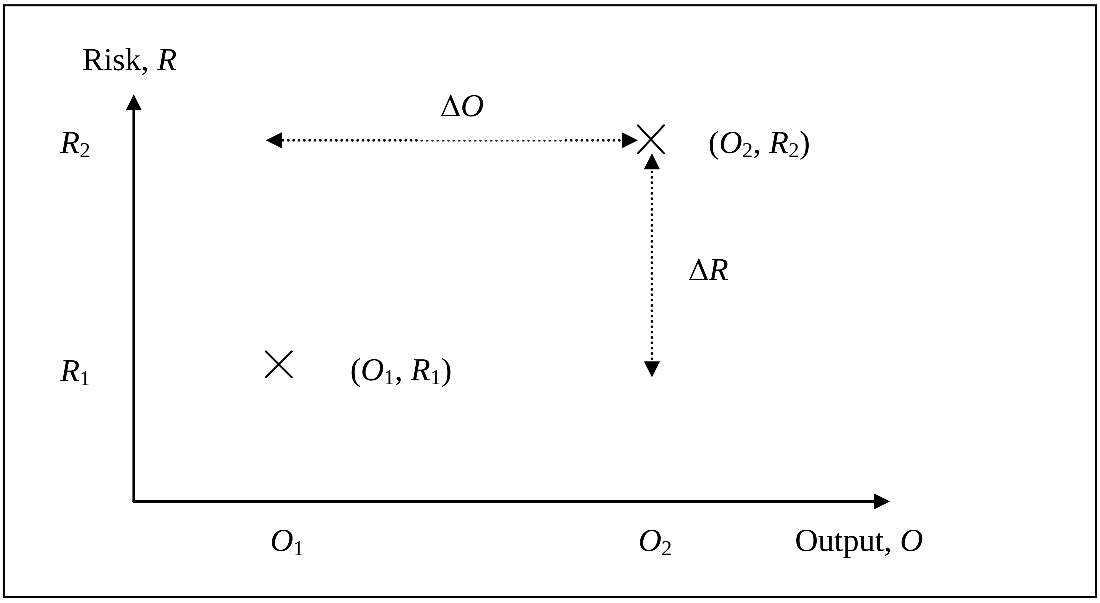

Figure 29 Diagram of current and new build risk and output levels. Current impacts = R_1/O_1, future impacts = R_2/O_2 and incremental impacts = $\Delta R/\Delta O$.

Chapter 14 Materials and Transportation Impacts

14.1 General Impacts in the Construction Materials Chain

One feature common to all electricity generating technologies is their need for construction materials. In this thesis the full chain of impacts associated with the production of such materials is assessed, in addition to the chain associated with the primary generating fuel. This entails estimating the impacts from the extraction of the raw materials, their subsequent manufacture and finally their disposal or recycling. Also included are the impacts from transportation processes associated between each of these stages.

Here, the impacts specific to each generating technology will not be assessed. Rather, the impacts will be determined per unit weight of construction material. These figures can then be applied to each technology by multiplying them by the quantity of material required for the generation of one unit of electrical energy. As discussed above, the unit of energy is taken as the gigawatt-year (GWa), and the unit of material weight is the megatonne (or million tonnes), given the symbol Mt. Impacts will be presented in terms of the exposure rate, measured in fatalities/Mt, and the associated loss of life expectancy resulting from a single exposure, measured in years/Mt. The hazard elimination premium (HEP) will not be presented for the general material chain, but will be presented in subsequent chapters when the general material impacts are applied to specific technologies.

Clearly, it is not feasible to estimate the impacts associated with each different material required in the construction processes of each technology, as such construction typically requires a great number of materials. It is therefore necessary to simplify the analysis, and this is done by only including only those materials used in massive quantities, which is the same approach as taken by most other authors, see Ball et al (1994) [15], ExternE (1995) [77] and Ferguson (1989) [83]. What constitutes a "massive quantity" can be defined easily. As will be shown in the following sections, for the fossil and nuclear technologies, concrete and steel requirements are much greater than for other materials. For all facilities in the fossil and nuclear fuel chains, steel and concrete requirements are in the range 10^{-4} – 10^{-2}

Mt/GWa. The materials requiring the greatest quantities after these are copper and aluminium. These requirements lie in the range 10^{-6} – 10^{-5} Mt/GWa. Therefore the threshold will be taken as 10^{-4} Mt/GWa. Any materials required in quantities less than this will not be assessed for impacts. Such a threshold, however, does pose issues for the wind technologies, where many materials are required in quantities around this level. Although this increases the burden of the analysis, it is nevertheless important to quantify the impacts of these materials so as to ensure consistency.

For transportation processes, a slightly different approach is taken. Risks from transportation are taken as those arising from the movement of freight – either the primary fuel, or the construction materials. Not included are transportation impacts resulting from occupational commuting. Exclusion of such impacts can be justified because the impact is not incremental – if the employee was not commuting to the power station (or other facility in the fuel chain), he would be commuting to another location. Thus, additional fuel chain facilities are assumed not to increase the number of commuters, rather, it redirects them.

Freight impacts are then determined for trains and HGVs. The initial risk factor is the number of additional fatalities per unit load-distance. The load-distance is the product of the quantity of freight carried and the distance over which it is carried. The common unit for this is the "billion-tonne-kilometre", abbreviated Bt-km (although a more appropriate name that uses the SI prefixes would be gigatonne-kilometre, Gt-km, here the commonly accepted unit shall be retained). For transportation in the primary fuel chain, these risk factors can then be multiplied by the quantity and distance over which the fuel is carried, to give a risk factor in terms of additional fatalities only, which can then be used to calculate the additional hazard rate and loss of life expectancy. This is also done for transportation in the construction materials chain, but the risk factor is then normalised by the quantity of material required to obtain a transport risk in terms of additional fatalities per megatonne. These transport impacts are presented in the next section.

14.2 Impacts Resulting from Transportation

In this section the risk factors for the transportation of freight will be calculated. Risks are identified separately for freight carried on trains and freight carried by HGVs. To estimate the risks from HGVs, it is necessary to know the number of deaths caused by HGVs, the total distance travelled, and the total load carried. Only data for HGVs travelling within the UK is sought. The required data can be obtained from the Department for Transport, which gives details on quantity of HGV freight, the distance over which it is carried [64], the number of fatalities in which at least one HGV was involved [65], and the number of HGV drivers and passengers killed [66]. Data is available for the five years from 2005 to 2009, and is shown in Table 17. Over this time the there has been 754 Bt-km of freight moved, 1,976 fatalities resulting from accidents involving at least one HGV, and 183 fatalities to HGV drivers and passenger fatalities. This raises the question about which fatality statistic is most appropriate to use. If the number of fatalities from accidents involving HGVs are used, then the exposure rate is 2.62 fatalities/Bt-km, whilst if the number of HGV drivers and passengers is used, the figure is 0.24 fatalities/Bt-km. The former figure will be an overestimate, as not all accidents involving HGVs are caused by HGV drivers, whilst the latter figure will be an underestimate, as fatalities to other members of the public caused by HGV drivers are not included. Therefore, these two values will be used as the high and low estimate for this risk. The central value is therefore 1.43 fatalities/Bt-km. The loss of life expectancy then ranges from 9.6 – 103.6 years/Bt-km

Similar data for freight trains can be obtained from the Office for Rail Regulation [154], [155], as well as again from the Department for Transport [67]. The relevant data is shown in Table 18 and Table 19. However, as with HGVs, issues arise with the apportionment of fatalities. Data is available for all fatalities to staff, passengers, trespassers and those resulting from suicides. To assign an exposure rate to freight, fatalities to passengers and suicides were excluded, but fatalities to trespassers and staff were included in the high risk estimate. This is because freight trains do not carry any passengers, but do sometimes run through built up areas where there is a risk of members of the public trespassing onto the track. The included fatalities are then apportioned to freight by multiplying by the ratio of freight distance travelled to all freight and passenger distance travelled, as shown in Table 18. Over the period 2005-2009, this results in an estimated 162 fatalities. The high exposure rate is then 1.55 fatalities/Bt-km. To estimate the low end of the risk estimate, it is assumed that no deaths are caused by freight. This is because many freight trains often move at fairly slow speeds away from built up areas, and so risks of accidents are much lower than in passenger trains. Therefore the low exposure rate is zero. The central rate is therefore 0.77 fatalities/Bt-km. The loss of life expectancy is 0 – 61.2 years/Bt-km. These exposure rates and loss of life expectancies are summarised in Table 20.

14.3 Impacts Resulting from the Use of Steel

Steel is one of the most fundamental materials used in construction. Although there are many different types of steel, each requiring different methods of production, a general impact chain will be used here that is taken as being applicable to all construction steel used in power plants and other related facilities. The process of making steel begins with the extraction of iron ore and coal. However, currently there is little iron ore mined in the UK, and imports are relied upon for steel production. Imports come from many different locations, making it difficult to ascribe hazard rates to this activity. Indeed, for many countries that produce substantial amounts of iron ore, safety statistics are not available. For these reasons, it has been assumed that the risk of quarrying iron ore is equal to that experienced in the UK stone quarrying industry. This assumption is justified because, in the context of quarrying, iron ore is similar to ordinary stone. Quarrying exposes individuals to four kinds of risk: Immediate occupational fatalities resulting from accidents in the quarry, delayed occupational fatalities from silicosis – a lung disease caused by the inhalation of rock dust containing silica, delayed occupational fatalities from radiation exposure (from radioactive rocks), and delayed public fatalities from particulate matter emissions from industrial machinery, and from the quarrying process itself. The risk estimates can be obtained from data on production of quarried rock, available from the UK Minerals Yearbook 2010 [26]; the number of fatalities in the quarrying industry, available from the Health and Safety Executive (HSE) [105]; the particulate matter emissions from the UK quarrying industry, available from DEFRA (2009a) [58] and (2009b) [59]; and the radioactive dose to workers in the quarrying industry, available from HSE's Central Index of Dose Information, see

HSE (2004a) [99]. Silicosis impacts are calculated using the method shown in Appendix C.

Stone production figures are shown in Table 21, the relevant minerals have been taken as igneous rock, limestone, dolomite and sandstone. Although there are other rocks that are quarried in the UK, these account for the majority of the production. Over the most recent five years, there has been 718 Mt of stone quarried in the UK.

The fatality statistics for this industry are shown in Table 25. These statistics fall under the HSE classification of “extractive” and sub-classification of “other mining and quarrying”. The fatalities are further designated as either “quarrying of stone for construction”, “operation of sand and gravel pits”, “mining of chemical and fertiliser minerals”, or “other mining and quarrying not elsewhere classified”. This final category includes fatalities in which there was not enough data to be able to classify the fatality appropriately. Over the five year period between 2005/06 and 2009/10, two fatalities were included in this section. It will be assumed that of these two, one can be attributed to “quarrying of stone for construction”, whilst the other can be attributed to “operation of sand and gravel pits”. This is done because the risk estimates are not just for quarrying of stone used for construction, but for all mineral ores as well, and so ascribing one of the two unclassified fatalities helps to avoid underestimating the risk in this respect. The other unclassified fatality is ascribed to the operation of sand and gravel pits so as not to underestimate the risk of quarrying sand and gravel, which is used for manufacturing concrete, as will be explained in the next section.

There have therefore been five fatalities in the stone quarrying industry over the most recent five years. The 95% confidence limits can be calculated using Poisson statistics. These can be computed from the inverse chi-square distribution, the values of which can be readily obtained in most spreadsheet programs, for example, see [142]. The only required information for calculating the 95% confidence interval is the number of observed fatalities. For stone quarrying, where there have been five observed fatalities, the confidence limits are approximately 1.62 – 11.67 fatalities. The exposure rate, expressed as the number of fatalities per Mt, is 0.002 – 0.016 fatalities/Mt. The loss of life expectancy associated with this exposure rate can then be calculated. For zero discount rate and assuming a uniform working population distribution between ages of 20 and 60, the loss of life expectancy for a short exposure is 0.09 – 0.64 years/Mt.

The loss of life expectancy resulting from exposures to stone dust, which causes silicosis, is calculated in Appendix C. The high and low estimates are shown to be 5×10^{-5} – 0.01 years/Mt.

The impacts from radiation exposure for the quarrying industry are estimated from the HSE's Central Index of Dose Information [99], which although discontinued in 2004, provides estimates of collective dose exposures to a wide number of industries. For 2004, the collective dose to those in the quarrying industry was 28 man-mSv. Although this figure is now quite dated, it will nevertheless be used as the best available estimate of the current dose commitment of the industry. It was decided not to average available data from previous years, as any trend would likely not be representative of current exposures. Also, no attempt has been made to quantify the uncertainty of this datum. This means that only a single figure will be presented for this radiological impact. When taking all of the above considerations into account, it is apparent that the quality of this datum is quite poor, and so the figures must be viewed with caution. However, as will be shown, the impact arising from delayed radiological impacts in the quarrying industry is quite small when compared to other impacts, and so the poor datum quality is relatively unimportant. A collective dose of 28 man-mSv in the quarrying industry can be re-expressed as 9.6×10^{-5} man-Sv/Mt. The loss of life expectancy with this exposure is then 7.1×10^{-5} years/Mt.

The final impact from quarrying results from public exposure to pollution. Section 5.9 describes how it is possible to determine the collective exposure to increased concentration levels from knowledge of the emission rate only, see equation (5.73). Emission rates of PM10 are published by DEFRA for a wide range of UK industries see DEFRA (2009a) [58]. However, as was discussed in section 5.9, the main indicator of health detriment resulting from emissions of pollutants is now considered to be PM2.5 emissions, which are a subset of PM10 emissions. It is therefore necessary to estimate the fraction of PM2.5 in the PM10 emissions. This can be determined again from DEFRA, but in a separate publication (see DEFRA (2009b)) [59]. In some industries, the PM2.5 data is given explicitly. However, for the quarrying industry this is not the case. To estimate the PM2.5 fraction, it was noted that for all industrial production processes, the fraction of PM2.5 in PM10 is given as 31%. Hence, this figure will be used for the PM2.5 content of PM10 emissions from the quarrying industry. Over the period 2004-2008, for which most recent data was available, the PM10 emissions from quarrying were 41.6 kilo-tonnes, so that the PM2.5 emissions were 12.9 kilo-tonnes. As these figures relate to the activities of the entire quarrying industry, and not just stone quarrying, the emissions are normalised against all quarrying production, including aggregates, from 2004-2008. The relevant data is shown in Table 22. Over this period, about 1,445 Mt of material was produced by UK quarrying activities. The PM2.5 emissions, expressed in terms suitable for equation (5.73), are then 5.7×10^4 μg/s/Mt. Using the equation, the collective exposure to increased concentration of pollutants, are 1.7×10^3 man-μg/m^3/Mt. This data is summarised in Table 32. The high and low risk factors for exposures to increased concentration levels, as derived in section 5.9 can then be used to determine the loss of life expectancy from quarrying PM2.5 emissions, which is 6.0 – 31.5 years/Mt. All of the above impacts associated with extraction of stone, which is used as a proxy indicator for iron ore extraction for steel, are summarised in Table 34.

The impacts of extracting coal are similar to those of extracting stone. There are occupational immediate fatalities from mining, occupational delayed fatalities from coal dust (which causes coal worker's pneumoconiosis (CWP)), and radiation exposure. The risks to the public are negligible as there are few emissions of PM2.5 from coal mines. There are, however, major catastrophe risks, in which large numbers of coal miners can be killed. These are classed separately from individual mining fatalities. These abnormal risks also have financial costs associated with them, which will also be estimated.

Coal production figures are shown in Table 22. From 2006 to 2010, there was about 87.3 million tonnes of coal mined in the UK.

As with stone quarrying, the fatality statistics for coal mining can be estimated from the HSE. There have been 12 fatalities over the period 2005/06 to 2009/10 that were classed by the HSE under "mining of coal and lignite; extraction of peat" in the extractive classification. Of these, 11 were due to coal mining, and one was due to extraction of peat. These are shown in more detail in Table 26. Therefore, over this period, 11 fatalities were associated with the production of 87.3 million tonnes of coal, so that the exposure rate is 0.13 fatalities/Mt. Using Poisson statistics, the 95% confidence limits for a count of 11 is 6.2 – 21.0 fatalities, so that the exposure rate ranges from 0.07 to 0.24 fatalities/Mt. The associated loss of life expectancy is 2.8 – 9.5 years/Mt.

The loss of life expectancy resulting from exposures to coal dust is calculated in Appendix C, along with the silicosis estimates from stone quarrying. The loss of life expectancy ranges from 0.01 – 5.4 years/Mt.

The radiation exposure to coal miners can again be determined from HSE statistics, as was the case with quarrying. The collective dose to all miners in 2004 was 0.3 man-Sv. This figure will be taken as applying to just coal miners, which means it will be an overestimate. However, the impact from this source of risk is not very large when compared to other sources of risk. The normalised collective dose is 0.01 man-Sv/Mt, and the loss of life expectancy is 0.01 years/Mt. No uncertainty is presented, so these figures must be viewed with caution.

Coal mining also carries the additional risk of a major accident resulting in multiple fatalities. In order to quantify this risk, data has been used from the ExternE NEEDS project [82], which presents historical data on energy related accidents resulting in multiple fatalities. For the European region, for the time period 1970 – 2005, there were 41 large coal mining accidents (defined as resulting in at least five fatalities), resulting in 942 fatalities. The 95% confidence limits are given as 0.13 – 0.144 fatalities/GWa. To convert this to fatalities/Mt, the figures are divided by the energy content of coal. This can be determined from DECC statistics [53], which shows that, for the UK over the period 2006 – 2010, 87.3 Mt of coal was used to produce 26.1 GWa of electrical energy. The energy content of coal is therefore 0.3 GWa/Mt. The number of fatalities resulting from major coal mining accidents in the EU is then

0.039 – 0.043 fatalities/Mt. The resulting loss of life expectancy is 1.5 – 1.7 years/Mt. It must be noted that these statistics use data over a long period. This is necessary, as large accidents are by their nature rare, and so using only the most recent five years is not sufficient to estimate these risks. However, using data from 1970 may result in the risk being overestimated, as there has been a trend towards over improving levels of safety. Nevertheless, given these difficulties, the available data represents the best estimate of the current risk level from major coal mining accidents. There is also another risk associated with large coal mining accidents – that of resulting financial costs. This impact can be estimated using the J_2-value framework. Data was taken from Sovacool (2008) [179], which details the costs of a large number of energy-related accidents over the period 1907-2007. Data was used from 1970-2007, so as to give similar risk levels to the fatality data. The data is also for global accidents, although the database probably omits a number of accidents in countries where safety records are sparse. Over this period, there were 25 coal mining accidents, resulting in a combined cost of about £160M. The cost per accident was therefore £6.4M. The frequency of such accidents is around 0.002 Mt^{-1}, so that the expected loss is £12,000 /Mt. In order to determine the maximum impact, it is necessary to multiply this figure by the risk multiplier, $m_{r.\max}$. The majority of the coal mining accidents resulted in losses that were below £5M. For a typical extractive company, this represents a small amount of initial assets. In such situations, the risk multiplier is close to unity. In addition, there were a few accidents where the cost was substantially greater than £5M. These accidents would represent a greater threat to the organisation's assets, and so would have a greater risk multiplier of around 1.2-1.5 (e.g. see the example in section 11.5). However, when averaging over all accidents, the risk multiplier would be very close, or less than, unity. Hence a risk multiplier of $m_{r.\max}= 1$ will be used. Therefore, the maximum reasonable spend on eliminating this financial risk, or "financial HEP", is £12,000 /Mt. The risks from coal extraction are summarised in Table 34.

To derive the impacts of the extraction of iron ore and coal in terms of the amount of steel produced, it is assumed that, for every tonne of steel produced, it is necessary to extract 1.6 tonnes of iron ore, and 1 tonne of coal, see Ball et al (1994) [15]. Thus, to estimate the impact per Mt of steel, the results of Table 34 need to be multiplied by 1.6 for iron ore, and 1.0 for coal.

Following extraction, the next stage in the material chain is manufacturing. The manufacturing of steel is associated with two impacts: occupational immediate fatalities, and delayed public fatalities from pollution. It is first necessary to estimate the amount of material produced. Most statistics tend to put iron and steel together, due to the similar nature of the material. Therefore, the production figures will be for both iron and steel. Production figures for various metals are shown in Table 23, although only data from 2005 to 2009 is available. Over this period there was 114.8 Mt of iron and steel produced.

The HSE fatality statistics for iron and steel manufacturing are classed under "basic metals" in the manufacturing section. There have been 10 fatalities over the period 2005/06 to 2009/10 involved with iron and steel manufacture. These are shown in more detail in Table 28. The central exposure rate is then 0.09 fatalities/Mt, and the 95% confidence limits are 0.04 to 0.16 fatalities/Mt. The loss of life expectancy is then 1.65 – 6.33 years/Mt.

Public pollution fatalities from iron and steel manufacture can be estimated from Table 31, where the collective exposure to increased concentration levels is 1.3×10^4 man-$\mu g/m^3$/Mt. This can be calculated to give a collective loss of life expectancy of 46.4 – 241.2 years/Mt.

After the facility for which the steel is being used has been decommissioned, it is assumed to be taken to a recycling facility. This stage also carried risks. The only type of risk associated with the recycling of metal is that of occupational immediate fatalities. To estimate this risk, it is necessary to determine the quantity of metal recycled, and the number of fatalities that have occurred in this industry. Recycling figures are available from DEFRA (2010) [60], for the years 1999 to 2008. In order to give figures consistent with other data, an estimate for the recycling quantity for 2009 has been produced by assuming the growth from 2007 to 2008 continues for 2009. The data is shown in Table 24. Over the period 2005 – 2009, there was 2.23 Mt of metal recycled. HSE statistics give the number of fatalities for recycling. Over the time period 05/06 to 09/10 there was 10 fatalities attributed to the recycling of metal waste. The exposure rate is therefore 4.48 fatalities/Mt, and the 95%

confidence limits are 2.15 – 8.24 fatalities/Mt. The associated loss of life expectancy is 84.9 – 325 years/Mt.

The final stages in the materials chain that needs estimating for steel are the transport processes. Section 14.2 derived the general exposure rates in terms of the number of additional fatalities per Bt-km. To derive a transport exposure rate specific to the manufacture of one million tonnes of steel, it is necessary to define each of the transport processes, the distance travelled for each one, and the quantity of material carried. The distance travelled will be assumed to be some nominal figure representative of the actual distance travelled.

The first stage will be the transportation of iron ore. Since iron ore is imported, the material is assumed to be moved from a generic port to the manufacturing plant. This distance is taken as 150 km. As 1.6 Mt of iron ore is required for every Mt of steel, the total load distance is 0.24 Bt-km/Mt. It is assumed that 70% of this journey is by train, and 30% is by road. The average exposure rate is therefore 0.97 fatalities/Bt-km (95% C.L.: 0.07 – 1.87). The loss of life expectancy associated with this exposure rate is 2.88 – 73.9 years/Bt-km. Using the above load-distance, the loss of life expectancy is then 0.690 – 17.7 years/Mt.

Another stage is the transportation of the coal. It will again be assumed that the transportation is 30% by road, 70% by rail. The distance from the coal mine to the manufacturing plant is assumed to be 100 km (mines are assumed to be closer than ports to the plant), and load is 1 Mt of coal per Mt of steel. The load-distance is then 0.1 Bt-km/Mt, and the loss of life expectancy is 0.288 – 7.39 years/Mt.

Once the steel is manufactured, it is assumed to be transported 200 km to the relevant facility where it is used for construction. The same exposure rate is taken, but this time with a load-distance is 0.2 Bt-km. The loss of life expectancy is then 0.575 – 14.8 years/Mt. The same assumptions apply post-decommissioning, where the steel is assumed to be transported 200 km to the recycling plant. Hence, the loss of life expectancy will be the same for this stage. All of these figures are immediate fatalities. However, they will occur to both workers and members of the public, but it is not known in what proportion. Therefore, it will be assumed that 50% of the fatalities are to workers, and hence are immediate occupational fatalities, and 50% are to members of the public, therefore being classed as immediate public fatalities.

One other source of risk that has not yet been discussed for transport is from the emissions of PM2.5. The collective exposure rates are listed in Table 33. The total load-distance for each of the above processes can be calculated for HGV and train pollution emissions, which then allow the impact to be calculated. The loss of life expectancy for HGVs is 2.12 – 11.0 years/Mt, whilst for trains it is 3.38 – 17.6 years/Mt.

All of the steel impacts discussed above are summarised in Table 36.

14.4 Impacts Resulting from the Use of Concrete

Another fundamental construction material is concrete. As with steel, this material is usually used in large amounts in any construction project. The process of manufacturing concrete first involves the quarrying of stone, sand and gravel. Sand and gravel is usually collectively referred to as “aggregates”. One Mt of concrete is assumed to be composed of 0.26 Mt of aggregates and 0.53 Mt of stone. The remaining 0.21 Mt is water and air. Of the 0.53 Mt of stone, 0.12 Mt is needed to first manufacture cement. The cement is then combined with the other materials to manufacture concrete. After decommissioning, it is assumed that the concrete will not be recycled, instead being disposed as waste.

Many of the risk estimates have already been derived in the preceding section. The risks involved with the quarrying of stone have been discussed, as they were used as a proxy measure for iron ore extraction risks. The risks, per Mt of stone, are shown in Table 34. To convert these into risks per Mt of concrete, it is necessary to multiply them by 0.53. This table also shows the risks of quarrying aggregates. These are taken from the production figures and fatality statistics shown in Table 22 and Table 25, where it is shown that over the period 2006 – 2010, there has been 403.8 Mt of aggregates produced, and there have been four fatalities to workers in this industry. The central value for the immediate occupational exposure rate is therefore 0.01 fatalities/Mt, and the 95% confidence limits are 0.003 – 0.025. The loss of life expectancy is 0.11 – 1.00 years/Mt. The quarrying of sand and gravel is also assumed to cause silicosis. The risk figures are the same as stone quarrying, which was shown to result in a loss of life expectancy of 5×10^{-5} – 0.01 years/Mt. The occupational radiological delayed impacts and the public delayed impacts from pollution are also equal to the figures for stone quarrying, as the data relate to the whole of the quarrying industry, which includes both stone quarrying and aggregates quarrying. Table 34 summarises the impacts per Mt of aggregates. The risks per Mt of concrete are then these figures multiplied by 0.26.

The manufacturing process is associated with immediate occupational fatality risks and delayed public pollution fatality risks. Immediate occupational fatality risks arise from the manufacture of both cement and concrete. The amount of these materials produced over the period 2005 – 2009, is shown in Table 23. There has been 52 Mt of cement and 106 Mt of concrete manufactured over this period. Table 30 shows the fatalities involved with the manufacturing. There has been one fatality in cement manufacture and five fatalities in concrete manufacture. The loss of life expectancies are then 0.02 – 4.2 years/Mt for cement manufacture and 0.61 – 4.4 years/Mt for concrete manufacture. To convert the cement figure to a value per Mt of concrete, it is necessary to multiply these values by 0.12. In addition, there are also public pollution risks associated with cement manufacture (but not concrete). The data is shown in Table 31, which gives the collective exposure as 131 man-$\mu g/m^3$/Mt. The loss of life expectancy associated with this impact is 0.47 – 2.5 years/Mt. These impacts are summarised in Table 35.

The final stage in the concrete chain is waste disposal. The risks associated with this industry are immediate occupational fatalities and public pollution fatalities. Data on the quantity of waste produced is presented in Table 24, which shows that there has been 269 million tonnes of waste produced over the period 2005 – 2009. Table 30 shows the number of fatalities associated with waste processing. There have been 22 such fatalities over the period 2005/06 to 2009/10. The exposure rate is therefore 0.04 – 0.12 fatalities/Mt, and the loss of life expectancy is 1.62 – 4.90 years/Mt. To estimate the impacts from pollution emissions, data from Table 32 is used, which shows that the collective exposure is 2.8×10^4 man-$\mu g/m^3$/Mt. The associated loss of life expectancy is 101 – 523 years/Mt. The risks from waste disposal are summarised in Table 35.

The other stage in the concrete chain is transportation. The transportation processes include: shipping the stone used in the cement from the quarry to the cement factory, shipping the other stone from the quarry to the concrete factory, shipping the aggregates from the quarry to the concrete factory, shipping the cement to the concrete factory, shipping the concrete from the factory to the power plant, and shipping the concrete from the power plant to the waste disposal site. It will be assumed that the distance from the quarries to the cement/concrete factory is 33 km, and that this entire journey is carried out by HGVs, as was assumed by Ferguson (1989) [83]. The loss of life expectancy associated with HGV transport is given in Table 20, as 9.6 – 103.6 years/Bt-km. For transporting stone to the cement plant, the load-distance is 0.004 Bt-km per Mt of concrete. For transporting stone to the concrete plant, the load-distance is 0.014 Bt-km per Mt of concrete, whilst for transporting aggregates to the concrete plant, the load-distance is 0.009 Bt-km per Mt of concrete. The respective loss of life expectancies are 0.04 – 0.41, 0.13 – 1.40 and 0.08 – 0.89 years/Mt. It will be assumed that the distance between the cement and the concrete plant will be small, so that the impacts can be ignored. For transporting concrete from the manufacturing plant to the power plant (or other related facility), the same risk factors as for steel transportation to the power plant will be used. This transportation stage resulted in a loss of life expectancy of 0.58 – 14.8 years/Mt. The same risk factors will again be used to estimate the impacts resulting from transportation from the power plant to waste disposal facility.

The loss of life expectancy from PM2.5 emissions can be calculated from data in Table 33, and from the above load-distances. The loss of life expectancy is 3.1 – 16.0 years/Mt for HGVs, and 5.4 – 28.1 years/Mt for trains.

The concrete impacts are summarised in Table 37.

14.5 Impacts Resulting from the Use of Non-Ferrous Metals

Although steel and concrete are the materials used in largest quantities in most construction projects, it is necessary to estimate the impacts of some other materials that were also found to be used in large quantities for the wind technologies. Several of these materials are non-ferrous metals: copper, lead, aluminium and zinc. The material chains of these metals are similar to that of steel. The process begins with extraction of the metal ore. This stage will be estimated using the stone risk factors, but will be scaled by the quantity of ore required to manufacture one million tonnes of copper. The next stage is manufacturing, where there will be public delayed impacts from pollution emissions. There are also immediate occupational fatality risks at this stage. However, this risk was only found to be significant for aluminium manufacture. It is assumed that all the ferrous metals can then be recycled after the facility has been decommissioned.

For transportation, it is assumed that the metal ores are shipped from a port to a manufacturing plant. The finished metal is then shipped from the plant to the power station. After decommissioning the metal is then shipped to the recycling facility. As has previously been discussed, there are immediate fatality risks and public delayed pollution risks associated with these impacts.

The extraction of raw materials for the manufacture of copper, lead, aluminium and zinc all involved the quarrying of the relevant ores. Therefore, it will be assumed, as with iron ore, that the risks derived for the quarrying of stone can be applied to these materials. These risks are shown in Table 34, where they are presented as loss of life expectancy per Mt of stone, or per Mt of ore for metals. These then need to be converted to a per Mt of manufactured metal. To do this, it is necessary to estimate the quantity of ore needed to obtain 1 Mt of metal. This can be determined from knowledge of typical grades of ores, which gives the quantity of metal per Mt of ore. Average grades are estimated from [167], [168] and [170], which gives the average grade of copper as 1.3%. Lead and zinc ores are usually mined together with average grades of 5%. It is assumed that lead and zinc occur in these ores with equal abundance, so that the average grade for both is 2.5%. The average grade for aluminium, which is obtained from bauxite ore, is taken as 25%. Thus, in order to convert the stone risk factors into non-ferrous metal risk factors, it is necessary to multiply by the inverse of these grades, namely; 77, 40, 4 and 40 for copper, lead, aluminium and zinc, respectively.

To estimate the delayed public pollution impacts from the manufacturing process, data from Table 31 can be used. The impacts in terms of years of lost life expectancy per Mt of metal are then shown in Table 35. Also shown are the immediate occupational impacts associated with the manufacturing of aluminium, which was the only non-ferrous metal found to pose significant risks, resulting from the one fatality shown in Table 28. Although there were no fatalities observed for the manufacture of other metals, this does not necessarily mean that there is no risk from this process. However, in the absence of further information indicating evidence to the contrary, it will be assumed that the immediate occupational risk from this source is negligible.

The risks for recycling will be the same as have been presented previously, as these risks are normalised against the total amount of metal to be recycled, and are not specific to the kind of metal. For transportation risks – the distances and mode of transport are also as given before. As with iron ore, it is assumed that the ore is imported from abroad, as relatively small amounts of ore are actually extracted in the UK. The distance from the port to the manufacturing plant is taken as 150 km, which is 70% on train and 30% on road. The distance from the manufacturing plant to the power station, and from the power station to the recycling plant is assumed to be 200 km, again with 70% on train and 30% by HGV. The risk factors for transport from manufacturing plant onwards will be the same as shown previously. The risk factor for transport from port to manufacturing plant are determined from the ore grades given above, which allow the load-distance per Mt of metal to be calculated. The impacts for these metals are summarised in Table 38, Table 39 and Table 40.

14.6 Impacts Resulting from the Use of Glass

Another material found to be used in large quantities for electricity generation by wind was glass, which is manufactured as glass fibres. The impacts of this material may also be evaluated using much of the data already presented.

One tonne of glass is assumed to require 0.75 tonnes of sand and 0.25 tonnes of limestone. These extraction risks are thus those from quarrying aggregates and stone, which have already been estimated. The figures in Table 34 can be converted into an impact per Mt of glass by multiplying the stone impacts by 0.25 and the aggregates impacts by 0.75.

There have been no observed fatalities for glass fibre manufacture, and so these risks will be assumed negligible. In addition, this industry does not produce any significant pollution emissions. Therefore the manufacturing part of the material chain has no impacts associated with it.

It is assumed that glass is disposed of as waste. The impacts associated with this activity have been quantified for the disposal of concrete, where it was discussed that there were immediate occupational impacts and delayed public pollution impacts. The waste disposal impacts for glass will be the same.

For the transportation process, the same risk factors will be assumed as for concrete. These are that the stone and sand are carried 33 km from the quarry to the factory entirely by HGV. The glass fibres are then carried 200 km to the power plant (or related facility) 70% by train and 30% by HGV. The same distance is also assumed for transport from the decommissioned plant to the waste disposal facility, using the same proportion of transport. There are then sufficient details to calculate the impact associated with the glass chain. These are presented in Table 41.

14.7 Impacts Resulting from the Use of Plastic

The final material found to be used in large quantities is plastic. The material chain for plastic is somewhat more complicated than the previous chains assessed. To make plastic, it is first necessary to extract oil and gas. This process involves immediate occupational risks, delayed radiological occupation risks and risks of major accidents. No data is available on PM2.5 emissions from this industry, and so it is assumed that they are negligible. Brine is also needed to supply chlorine used in the manufacturing process. It is assumed that obtaining brine carries negligible risks. One Mt of plastic is taken as requiring 0.33 Mt of oil, 0.16 Mt of gas and 0.74 Mt of brine [160]. To estimate the extraction risks, oil and gas are considered together, as these are often obtained together from offshore rigs. The number of offshore fatalities is given in Table 27, which is a summary of a more comprehensive list of energy related fatalities given in Table 86. The fatalities are divided into those occurring in small accidents, and those occurring in large accidents. This is because fatalities occurring in large accidents are classified as an abnormal operation impact. Over the period 2006 – 2010, there were nine fatalities from small accidents, and 31 fatalities from large accidents. A large accident is one in which at least five individuals are killed, as was briefly discussed in coal mining abnormal operation impacts. These fatalities are then normalised against the total weight of oil and gas produced. For oil, these figures are shown in Table 89. Over the period 2006 – 2010, 356 Million tonnes of oil was produced. For gas, estimating the weight produced is a little more difficult. Table 88 gives data on the energy equivalent of gas produced. Over the same period, there was 449 GWa equivalent of gas produced. To convert this to a weight, a figure of 1.73 billion cubic metres is taken as the volume of gas required to generate one GWa of energy [15]. The density of natural gas is then taken as 0.8 kg/m^3 [72]. The weight of gas per unit energy can then be calculated as 1.38 Mt/GWa. There was therefore 620 Mt of gas extracted over the period being assessed. The central exposure rate is therefore 0.007 fatalities/Mt, and the 95% confidence limits are 0.002 – 0.016 fatalities/Mt. The loss of life expectancy is 0.09 – 0.64 years/Mt. To convert this to a figure per Mt of plastic, it is necessary to multiply by 0.49 (the total proportion of oil and gas required in plastic).

Radiation impacts from gas and oil extraction can be estimated from the HSE's Central Index of Dose Information, as has been done for other extractive industries. The most recent datum gives the total dose exposure to offshore workers as 161 man-mSv, or 6.5×10^{-4} man-Sv/Mt. This results in a loss of life expectancy of 4.8×10^{-4} years/Mt.

Two estimates are available for the abnormal operation impact. This impact arises from large accidents in the offshore industry. These accidents typically involve helicopter crashes or capsized boats. The first estimate involves using large accident data from the UK over the period 2006 – 2009. It has already been noted that there were 31 fatalities. The loss of life expectancy associated with this impact is 1.2 years/Mt. The other estimate is from the ExternE project discussed above for major coal accident risks. From 1970 to 2005, there were 337 fatalities associated with the use of natural gas, and 1236 fatalities associated with the use of oil, in European countries. About 25% of the gas fatalities and 50% of the oil fatalities can be attributed to the extraction stage. The loss of life expectancy of this impact is 1.6 years/Mt. As this estimate is larger than the UK 2006 – 2009 data, it shall be adopted in the interests of conservatism. The 95% confidence limits are 1.5 – 1.7 years/Mt. These figures also need to be multiplied by 0.49 to derive the impact per Mt of plastic.

As with abnormal risks involved with coal mining, there is also a financial cost associated with large gas and oil accidents. Data from 1970-2007 (see Sovacool, (2008) [179]) indicate that globally, the average cost of gas accidents is £5.3M per accident. For oil accidents, the figure is much larger at £118M per accident. The frequency of gas accidents is around 0.005 Mt^{-1}, while for oil accidents the frequency is 0.003 Mt^{-1}. The combined expected loss from these risks are then about £354,000 /Mt. As with coal mining accidents, the majority of these accidents had costs below £5M, and there were few very costly accidents. A risk multiplier of $m_{r.\max}$= 1 will therefore be used. The financial HEP for this impact is then £354,000 /Mt. The risks from gas and oil extraction are summarised in Table 34.

The next stage of the plastic material chain is manufacturing. This results in immediate occupational impacts and delayed public impacts. HSE statistics show that there has been five fatalities associated with plastic manufacture between 2005/06 and 2009/10 [105]. To estimate the quantity of plastic manufactured an estimate from the British Plastics Federation of an annual production of 2.5 Mt is used [27]. As there is no other data available, it will be assumed that this figure is constant, so that over the five year period, 12.5 Mt of plastic was produced. The exposure rates are therefore 0.13 – 0.93 fatalities/Mt. The loss of life expectancy is 5.1 – 36.9 years/Mt. The collective exposure to PM2.5 from plastic manufacturing is given in Table 31 as 4.5×10^5 man-$\mu g/m^3$/Mt. The loss of life expectancy with this impact is 1,611 – 8,375 years/Mt.

It is assumed that after decommissioning, plastic is recycled. The recycling figures are for non-metallic products. The quantity of recycled products and fatalities associated with this industry are given in Table 24 and Table 30. Non-metallic recycling has exposure rates of 0.08 – 0.45 fatalities/Mt and the loss of life expectancy is 3.0 – 17.7 years/Mt. There are no pollution impacts.

The transportation processes are assumed as follows: shipping oil and gas from a port to a manufacturing plant. The load-distance is 0.074 Bt-km/Mt and 70% is by train and 30% is by rail. Brine is also shipped from a port to the plant. The transportation methods are the same, but the load distance is now 0.11 Bt-km/Mt. The finished plastic is then shipped to a power plant and then after decommissioning, to a recycling plant. The load distance for each journey is 0.2 Bt-km/Mt, and the transportation methods are again the same. A summary of the impacts associated with the plastics material chain is shown in Table 42.

HGV Statistics	Freight Moved (Billion tonne-kms)	Fatalities from accidents involving at least one HGV	HGV Drivers and Passenger Fatalities
2005	153	486	55
2006	156	419	39
2007	161	435	52
2008	152	368	23
2009	132	268	14
Total	754	1,976	183

Table 17 HGV statistics, from [64], [65] and [66].

Train Statistics	Freight Load Moved (Billion tonne-kms)	Total Freight Distance (million kms)	Total Passenger Distance (million kms)	Freight Fraction
2005	21.70	93.9	459.5	0.17
2006	21.88	73.8	464.0	0.14
2007	21.18	68.7	459.1	0.13
2008	20.63	63.6	479.3	0.12
2009	19.06	60.9	500.0	0.11
Total	104.45	360.9	2,361.9	0.15

Table 18 Train freight and passenger statistics, from [67] and [155].

Train Fatalities	All fatalities, excluding trespassers, suicides and passengers	All fatalities, excluding trespassers and suicides	All fatalities, Excluding suicides and passengers	Fatalities apportioned to freight
2005	23	33	238	40.4
2006	13	21	265	36.4
2007	20	27	224	29.2
2008	24	27	253	29.6
2009	11	15	240	26.0
Total	91	123	1,220	161.6

Table 19 Rail fatalities 2005-2009, from [154] and [155].

Transport Exposure Rates - Summary	Fatalities/Bt-km	Loss of Life Expectancy (years/Bt-km)
Road - HGVs	0.24 – 2.62	9.6 – 103.6
Rail - Freight	0 – 1.55	0 – 61.2

Table 20 Summary of transport exposure rates.

UK Stone Production (Million tonnes)	Igneous Rock	Limestone and Dolomite	Sandstone
2006	54.0	92.3	18.0
2007	58.9	91.1	16.8
2008	53.5	79.7	12.3
2009	44.6	63.3	12.3
2010	45.0	64.0	12.5
Sub-total	256.0	390.4	71.9
Total	718.3		

Table 21 UK production of stone, from [26].

UK Minerals Production (Million tonnes)	All Quarrying of Stone	Quarrying of Aggregates (Sand and Gravel)	Coal Production - Deep and Opencast Mines
2004	203.9	97.3	24.5
2005	197.2	94.7	20.0
2006	201.2	92.1	18.1
2007	203.1	93.2	16.5
2008	177.1	85.5	17.6
2009	145.1	66.2	17.4
2010	149.8	66.8	17.7
Total, 2004 – 2008	982.5	462.8	96.7
Total, 2006 – 2010	1275.0	403.8	87.3

Table 22 UK production of minerals, from [26].

UK Selected Manufactured Materials Production (Million Tonnes)	Cement	Concrete	Iron	Steel	Aluminium
2005	11.2	22.4	10.2	13.2	0.573
2006	11.5	23.0	10.7	13.9	0.565
2007	11.9	23.5	11.0	14.4	0.558
2008	10.1	20.1	10.1	13.5	0.473
2009	7.6	16.6	7.67	10.1	0.457
Total	52.3	106	49.7	65.1	2.63

Table 23 UK production of selected manufactured materials, from [26].

UK Quantities of Recycling and Waste (Million Tonnes)	Recycling of Metal	Recycling of Non-Metal	Production of Waste
2005	0.392	5.20	59.4
2006	0.438	5.61	56.5
2007	0.428	5.87	53.7
2008	0.467	6.13	50.9
2009	0.507	6.39	48.0
Total	2.23	29.2	269

Table 24 Quantities of recycling and waste production, from [60] and [61]. The 2009 recycling figures have been extrapolated from the growth between 2007 and 2008. Waste figures were only available from 2002 to 2009, so a linear interpolation was performed to estimate the figures in between these years.

UK Extractive Fatalities Under Classification "Other Mining and Quarrying"	Quarrying of Stone for Construction	Operation of Sand and Gravel Pits	Mining of Chemical and Fertiliser Minerals	Other Mining and Quarrying Not Elsewhere Classified	Total
2005-2006	1	1	0	0	2
2006-2007	1	0	0	1	2
2007-2008	1	0	1	0	2
2008-2009	0	2	0	1	3
2009-2010	1	0	0	0	1
Total	4	3	1	2	10
Total Attributed to Quarrying of Stone				5	
Total Attributed to Quarrying of Sand and Gravel				4	

Table 25 HSE fatality statistics for extractive industries classed under "other mining and quarrying". Here assumed that one "other mining and quarrying not elsewhere classified" is attributable to stone quarrying and one is attributable to sand and gravel quarrying, from [105].

UK Extractive Fatalities Under Classification "Mining of Coal and Lignite; Extraction of Peat"	Mining & Agglomeration of Hard Coal	Mining & Agglomeration of Lignite	Extraction & Agglomeration of Peat	Total
2005-2006	0	0	0	0
2006-2007	5	0	0	5
2007-2008	2	0	1	3
2008-2009	1	0	0	1
2009-2010	3	0	0	3
Total	11	0	1	12

Table 26 HSE fatality statistics for extractive industries classed under "mining of coal and lignite; extraction of peat".

UK Offshore Fatalities	Fatalities in Small Accidents	Fatalities in Large Accidents	Total
2006	2	7	9
2007	4	8	12
2008	0	0	0
2009	3	16	19
2010	0	0	0
Total	9	31	40

Table 27 UK offshore fatalities, 2006 – 2010, see Table 86 for further details.

UK Manufacturing Fatalities Under Classification "Basic Metals"	Manufacture and Casting of Basic Iron/Steel	Aluminium Production	Production and Casting of Other Metals	Total
2005-2006	2	0	0	2
2006-2007	1	1	2	4
2007-2008	3	0	0	3
2008-2009	4	0	0	4
2009-2010	0	0	1	1
Total	10	1	3	14

Table 28 HSE fatality statistics under classification "basic metals" in manufacturing section.

UK Manufacturing Fatalities Under Classification "Non-Metallic Mineral Products"	Manufacture of Flat Glass	Manufacture of Cement	Manufacture of Concrete	Manufacture of Other Non-Metallic Mineral Products	Total
2005-2006	0	1	2	4	7
2006-2007	1	0	0	1	2
2007-2008	0	0	1	1	2
2008-2009	0	0	2	0	2
2009-2010	0	0	0	1	1
Total	1	1	5	7	14

Table 29 HSE fatality statistics under classification "non-metallic mineral products" in manufacturing section.

UK Recycling and Waste Fatalities	Recycling of Metal and Waste Scrap	Recycling of Non-Metal Waste and Scrap	Wholesale of Waste and Scrap	Collection and Treatment of Other Waste
2005-2006	5	1	1	6
2006-2007	0	1	0	6
2007-2008	2	2	1	2
2008-2009	2	2	1	3
2009-2010	1	0	0	2
Total	10	6	3	19

Table 30 HSE fatality statistics attributed to recycling of metals and non-metals, and for waste the wholesale and treatment of waste.

PM2.5 Emissions for Manufacturing Industries (ktonnes/year)	Cement	Iron and Steel	Copper	Lead	Zinc	Aluminium	Plastic
2004	0.01	1.51	0.01	0.00	0.00	0.06	-
2005	0.01	1.31	0.01	0.01	0.00	0.06	-
2006	0.02	1.33	0.01	0.01	0.00	0.05	-
2007	0.02	2.07	0.01	0.00	0.00	0.04	-
2008	0.02	1.95	0.01	0.01	0.00	0.04	-
Total	0.08	8.17	0.05	0.02	0.01	0.25	-
Total, μg/s/ Mt	4.43×10^{3}	4.34×10^{5}	1.20×10^{5}	8.28×10^{4}	6.66×10^{4}	5.87×10^{5}	1.51×10^{7}
Collective Exposure, man-μg/m^3/ Mt	1.31×10^{2}	1.29×10^{4}	3.55×10^{3}	2.45×10^{3}	1.97×10^{3}	1.74×10^{4}	4.46×10^{5}

Table 31 PM2.5 emissions for manufacturing industries, and collective exposures, from [58], [59] and [160]. Figure for plastic production only available for a generic quantity of bulk PVC.

PM2.5 Emissions for Extractive and Disposal Industries (ktonnes/year)	Quarrying	Waste
2004	2.69	6.0
2005	2.57	6.0
2006	2.54	6.0
2007	2.54	6.0
2008	2.55	6.0
Total	12.90	42.0
Total, μg/s/Mt	5.66×10^{4}	9.42×10^{5}
Collective Exposure, man-μg/m^3/Mt	1.68×10^{3}	2.79×10^{4}

Table 32 PM2.5 emissions for extractive and disposal industries, and collective exposures, from [58] and [59].

PM2.5 Emissions for Various Industries (ktonnes/year)	HGV Transport	Trains
2004	6.0	0.59
2005	5.0	0.61
2006	5.0	0.62
2007	4.0	0.61
2008	4.0	0.62
Total	24.0	3.05
Total, μg/s/Bt-km	1.97×10^5	1.81×10^5
Collective Exposure, man-μg/m^3/Bt-km	5.82×10^3	5.35×10^3

Table 33 PM2.5 emissions from transportation processes, from [58] and [59].

Extraction Impacts – Summary (years/Mt)	Occupational Immediate Fatalities	Occupational Delayed Fatalities – Pneumoconiosis	Occupational Delayed Fatalities – Radiation	Public Delayed Fatalities - Pollution	Abnormal Operation
Stone Quarrying	0.09 – 0.64	5×10^{-5} – 0.01	7.1×10^{-5}	6.0 – 31.5	N/A
Aggregates Quarrying	0.11 – 1.00	5×10^{-5} – 0.01	7.1×10^{-5}	6.0 – 31.5	N/A
Coal Mining	2.8 – 9.5	0.01 – 5.36	0.01	-	1.54 – 1.7[a,b]
Oil and Gas Extraction	0.08 – 1.06	-	5×10^{-4}	-	1.47 – 1.66[a,c]

Table 34 Summary of impacts associated with extraction processes, in terms of years of lost life expectancy/Mt

a. All resulting in immediate occupational impacts.

b. In addition there is a financial HEP of £12,000 /Mt.

c. In addition there is a financial HEP of £354,000 /Mt.

Manufacturing, Recycling and Waste Disposal Impacts (years/Mt)	Occupational Immediate Fatalities	Public Delayed Fatalities - Pollution
Iron and Steel Manufacture	1.65 – 6.33	46.4 – 241
Cement Manufacture	0.020 – 4.34	0.474 – 2.47
Concrete Manufacture	0.621 – 4.46	-
Copper Manufacture	-	12.8 – 66.6
Lead Manufacture	-	8.85 – 46.0
Aluminium Manufacture	0.381 – 83.8	62.7 – 326
Zinc Manufacture	-	7.12 – 37.0
Plastic Manufacture	5.13 – 36.9	1610 – 8375
Waste Disposal	1.62 – 4.90	101 - 523
Metal Recycling	84.9 – 325	-

Table 35 Summary of manufacturing, waste disposal and recycling impacts.

Steel Impacts (years of lost life/Mt)	Immediate Fatalities[a]	Occupational Delayed Fatalities – Pneumoconiosis	Occupational Delayed Fatalities – Radiation	Public Delayed Fatalities – Pollution	Abnormal Operation
Extraction – Iron Ore	0.142 – 1.03	8.6×10^{-5} – 0.02	1.1×10^{-4}	9.68 – 50.3	-
Extraction – Coal	2.81 – 9.49	0.006 – 5.36	0.009	-	1.54 – 1.70[d, e]
Manufacture	1.65 – 6.33	-	-	46.4 – 241	-
Recycling	84.9 - 325	-	-	-	-
Transport (pre-construction)	1.55 – 39.9[b]	-	-	14.7 – 76.3	-
Transport (post – decomm-issioning)	0.57 – 14.8[b]			-[c]	-
Total (pre-construction)	6.15 – 56.8	0.006 – 5.38	0.009	70.8 – 368	1.54 – 1.70
Total (post – decomm-issioning)	85.5 – 340	-	-	-	-

Table 36 Summary of impacts associated with the steel material chain. Pre-construction impacts include extraction and manufacture processes, and any transport that occurs before the construction of the power plant. Post-decommissioning impacts include recycling and transport from the facility to the recycling plant.

a. Occupational impacts, unless otherwise stated.

b. 50% of this loss of life expectancy is assumed to occur to workers, and 50% to members of the public.

c. All transportation public pollution impacts assigned to pre-construction stage.

d. All resulting in immediate occupational impacts.

e. In addition is a financial HEP of £12,000 /Mt.

Concrete Impacts (years of lost life/Mt)	Immediate Fatalities[a]	Occupational Delayed Fatalities – Pneumoconiosis	Occupational Delayed Fatalities – Radiation	Public Delayed Fatalities – Pollution	Abnormal Operation
Extraction – Stone	0.05 – 0.34	2.8×10^{-5} – 0.01	3.8×10^{-5}	3.21 – 16.7	-
Extraction – Aggregates	0.03 – 0.26	1.4×10^{-5} – 0.003	1.9×10^{-5}	1.57 – 8.18	-
Manufacture - Cement	0.002 – 0.51	-	-	0.06 – 0.30	-
Manufacture - Concrete	0.61 – 4.37	-	-	-	-
Waste Disposal	1.62 – 4.90	-	-	101 - 523	-
Transport (pre-construction)	0.83 – 17.5[b]	-	-	8.47 – 44.1	-
Transport (post – decomm-issioning)	0.57 – 14.8[b]			-[c]	-
Total (pre-construction)	1.52 – 23.0	4.2×10^{-5}– 0.01	5.7×10^{-5}	13.3 – 69.3	-
Total (post – decomm-issioning)	2.19 – 19.7	-	-	101 - 523	-

Table 37 Summary of impacts associated with the concrete material chain. Pre-construction impacts include extraction and manufacture processes, and any transport that occurs before the construction of the power plant. Post-decommissioning impacts include waste disposal and transport from the facility to the waste disposal plant.

a. Occupational impacts, unless otherwise stated.

b. 50% of this loss of life expectancy is assumed to occur to workers, and 50% to members of the public.

c. All transportation public pollution impacts assigned to pre-construction stage.

Copper Impacts (years of lost life/Mt)	Immediate Fatalities[a]	Occupational Delayed Fatalities – Pneumoconiosis	Occupational Delayed Fatalities – Radiation	Public Delayed Fatalities - Pollution	Abnormal Operation
Extraction – Copper Ore	6.87 – 49.4	0.004 – 0.95	0.005	465 – 2420	-
Manufacture	-	-	-	12.8 – 66.6	-
Recycling	84.9 - 325	-	-	-	-
Transport (pre-construction)	33.8 – 867[b]	-	-	237 – 1230	-
Transport (post – decomm-issioning)	0.57 – 14.8[b]			-[c]	-
Total (pre-construction)	40.7 – 916	0.004 – 0.95	0.005	715 – 3720	-
Total (post – decomm-issioning)	85.5 – 340	-	-	-	-

Table 38 Summary of impacts associated with the copper material chain. Pre-construction impacts include extraction and manufacture processes, and any transport that occurs before the construction of the power plant. Post-decommissioning impacts include recycling and transport from the facility to the recycling plant.

a. Occupational impacts, unless otherwise stated.

b. 50% of this loss of life expectancy is assumed to occur to workers, and 50% to members of the public.

c. All transportation public pollution impacts assigned to pre-construction stage.

Lead/Zinc Impacts (years of lost life/Mt)	**Immediate Fatalities[a]**	**Occupational Delayed Fatalities – Pneumoconiosis**	**Occupational Delayed Fatalities – Radiation**	**Public Delayed Fatalities - Pollution**	**Abnormal Operation**
Extraction – Lead/Zinc Ore	3.57 – 25.7	0.002 – 0.50	0.003	242 – 1260	-
Manufacture of Lead(Zinc)	-	-	-	8.85 – 46.0 (7.12 – 37.0)	-
Recycling	84.9 - 325	-	-	-	-
Transport (pre-construction)	17.8 – 457[b]	-	-	127 – 659	-
Transport (post – decomm-issioning)	0.57 – 14.8[b]			-[c]	-
Lead(Zinc) Total (pre-construction)	21.4 – 483	0.002 – 0.50	0.003	378 – 1970 (376 – 1960)	-
Total (post – decomm-issioning)	85.5 – 340	-	-	-	-

Table 39 Summary of impacts associated with the lead/zinc material chain. Pre-construction impacts include extraction and manufacture processes, and any transport that occurs before the construction of the power plant. Post-decommissioning impacts include recycling and transport from the facility to the recycling plant.

a. Occupational impacts, unless otherwise stated.

b. 50% of this loss of life expectancy is assumed to occur to workers, and 50% to members of the public.

c. All transportation public pollution impacts assigned to pre-construction stage.

Aluminium Impacts (years of lost life/Mt)	Immediate Fatalities[a]	Occupational Delayed Fatalities – Pneumoconiosis	Occupational Delayed Fatalities – Radiation	Public Delayed Fatalities - Pollution	Abnormal Operation
Extraction – Bauxite	0.36 – 2.57	2×10^{-4} – 0.05	2×10^{-4}	24.2 – 125.8	-
Manufacture	0.38 – 83.8	-	-	62.7 – 326	-
Recycling	84.9 - 325	-	-	-	-
Transport (pre-construction)	2.30 – 59.1[b]	-	-	19.8 – 103	-
Transport (post – decomm-issioning)	0.57 – 14.8[b]			-[c]	-
Total (pre-construction)	3.04 – 145	2×10^{-4} – 0.05	2×10^{-4}	107 – 555	-
Total (post – decomm-issioning)	85.5 – 340	-	-	-	-

Table 40 Summary of impacts associated with the aluminium material chain. Pre-construction impacts include extraction and manufacture processes, and any transport that occurs before the construction of the power plant. Post-decommissioning impacts include recycling and transport from the facility to the recycling plant.

a. Occupational impacts, unless otherwise stated.

b. 50% of this loss of life expectancy is assumed to occur to workers, and 50% to members of the public.

c. All transportation public pollution impacts assigned to pre-construction stage.

Glass Impacts (years of lost life/Mt)	Immediate Fatalities[a]	Occupational Delayed Fatalities – Pneumoconiosis	Occupational Delayed Fatalities – Radiation	Public Delayed Fatalities - Pollution	Abnormal Operation
Extraction – Stone	0.02– 0.16	1×10^{-5} – 0.003	2×10^{-5}	1.51 – 7.86	-
Extraction - Aggregates	0.08 – 0.75	4×10^{-5} – 0.01	5×10^{-5}	4.54 – 23.6	
Manufacture	-	-	-	-	-
Recycling	2.98 – 17.7	-	-	-	-
Transport (pre-construction)	0.89 – 18.2[b]	-	-	8.62 – 44.8	-
Transport (post – decomm-issioning)	0.57 – 14.8[b]			-[c]	-
Total (pre-construction)	0.99 – 19.1	5×10^{-5} – 0.01	7×10^{-5}	14.7 – 76.3	-
Total (post – decomm-issioning)	2.19 – 19.7	-	-	101 – 523	-

Table 41 Summary of impacts associated with the glass material chain. Pre-construction impacts include extraction and manufacture processes, and any transport that occurs before the construction of the power plant. Post-decommissioning impacts include waste disposal and transport from the facility to the waste disposal plant.

a. Occupational impacts, unless otherwise stated.

b. 50% of this loss of life expectancy is assumed to occur to workers, and 50% to members of the public.

c. All transportation public pollution impacts assigned to pre-construction stage.

Plastic Impacts (years of lost life/Mt)	Immediate Fatalities[a]	Occupational Delayed Fatalities – Pneumoconiosis	Occupational Delayed Fatalities – Radiation	Public Delayed Fatalities - Pollution	Abnormal Operation
Extraction – Oil and Gas	0.04 – 0.52	-	2×10^{-4}	-	0.72 – 0.81[d,e]
Manufacture	5.13 – 36.9	-	-	1611 – 8380	-
Recycling	2.98 – 17.7	-	-	-	-
Transport (pre-construction)	1.11 – 28.4[b]	-	-	11.6 – 60.2	-
Transport (post – decomm-issioning)	0.57 – 14.8[b]			-[c]	-
Total (pre-construction)	6.28 – 65.8	-	2×10^{-4}	1623 – 8440	0.72 – 0.81
Total (post – decomm-issioning)	3.55 – 32.5	-	-	-	-

Table 42 Summary of impacts associated with the plastic material chain. Pre-construction impacts include extraction and manufacture processes, and any transport that occurs before the construction of the power plant. Post-decommissioning impacts include recycling and transport from the facility to the recycling plant.

a. Occupational impacts, unless otherwise stated.
b. 50% of this loss of life expectancy is assumed to occur to workers, and 50% to members of the public.
c. All transportation public pollution impacts assigned to pre-construction stage.
d. All resulting in immediate occupational impacts.
e. In addition is a financial HEP of £174,000 /Mt.

Chapter 15 The Nuclear Fuel Chain

15.1 Description of the Fuel Chain

The nuclear fuel chain describes each stage and activity involved in the production of electricity using uranium as the input fuel. The extraction phase involves the mining of uranium. As of 2009, around 57% of extracted uranium was mined using conventional underground and open cast techniques, and 36% is mined using leaching techniques. The countries that produce the most uranium are Kazakhstan, Canada, Australia and Namibia, see e.g. World Nuclear Association (2011b) [208]. Most conventional mines also have on site a milling facility where the ore is crushed, and the uranium is separated and packaged.

The preparation phase of the fuel chain involves conversion, enrichment and fabrication. After the uranium has been packaged, it is sent to a conversion facility. In the UK, this is done at the Springfields site near Preston in Lancashire, although much imported uranium is prepared abroad. At the conversion facility, the packaged uranium is dissolved in acid to allow any impurities to be removed. The solution is then treated to increase concentration before being transported to the enrichment facility, which in the UK is done at Urenco's Capenhurst site near Chester. At the enrichment facility, the concentrated uranium solution is heated until it is gaseous, whereupon it is fed into a centrifuge. The lighter uranium-235 isotope then concentrates near the centre of the centrifuge, while the heavier uranium-238 isotope concentrates at the end. This process can be repeated until the desired level of enrichment is achieved. After enrichment, uranium fuel is then sent to fabrication plants. In the UK this is again done at Springfields. Here, the fuel is manufactured into a form suitable for use in a reactor.

The fuel is then transported to the nuclear power plant. Currently, the UK has three types of operational nuclear plants: two Magnox plants, seven advanced gas-cooled reactors (AGRs), and one pressurised water reactor (PWR). The main differences between these designs are the substances used for cooling and moderating the nuclear reaction. For example, in AGRs, the moderator is made of graphite, and cooling is achieved using carbon dioxide, whilst in PWRs water is used for both cooling and for the moderator. New UK nuclear power stations built in the foreseeable future are expected to be PWRs. There are currently two variants of the PWR that are being assessed by the Health and Safety Executive for new UK build: the EPR and the AP1000.

A by-product of the electricity generation process is spent fuel. This can be stored underwater, sent for disposal or reprocessed. Reprocessing of spent fuel occurs at Sellafield in Cumbria, which is one of the few large reprocessing facilities in the world. During this stage of the fuel chain, fissile materials are recovered from the spent fuel. These materials can then be used to provide fresh fuel for use in power plants. Reprocessing also reduces the volume of highly radioactive waste substantially, making disposal easier and safer.

The final stage of the fuel chain is waste disposal. Nuclear waste is classified into three types: low-level waste (LLW), which is only slightly contaminated, and does not usually need any special precautions; intermediate-level waste (ILW), which contains higher levels of radioactivity, and requires processing to minimise the associated dangers; and high-level waste (HLW), which is very radioactive and has to be stored for decades to reduce the radioactivity before being disposed of. In the UK, LLW is currently disposed of at the Low-Level Waste Repository in Drigg, near Sellafield. There is no current facility for disposing of other wastes, and they must be stored until one is available. The Nuclear Decommissioning Authority (NDA) is currently planning to construct two deep repositories for waste disposal, see Nirex (2005) [140]. One repository would be for LLW and ILW, whilst the other would be for HLW and other spent fuel.

The nuclear chain is a complex electricity system, and each stage needs careful consideration. One of the most distinguishing features of the nuclear chain is the presence of radioactive material, which has the potential to cause catastrophe. These risks have implications for both workers and the public. The examination of the risks will be broken down into the following stages: first the plant parameters will be defined for both existing and prospective facilities. Then the risks will be evaluated at each fuel chain stage within the system boundary and will be classed according to whether the risks are to members of the public or to workers, and whether they are immediate or delayed risks. The risk of a large nuclear accident at the generation stage, which results in physical risk to workers and members of the public, as well as causing environmental damage, will also be classed separately.

15.2 Plant Parameters

The assumptions that were necessary to make in regards to the fuel chain facilities will now be stated. These related to the lifetimes for construction, operation and decommissioning, the power plant capacity and its capacity factor. Table 43 lists all UK power plants that are currently operating or undergoing decommissioning, as well as the dates of other facilities relevant to the UK nuclear fuel chain. These include the enrichment facilities at Capenhurst - one of which is being decommissioned by the Nuclear Decommissioning Authority (NDA), and one which is still operational, and is operated by Urenco UK Ltd. Also included are the conversion and fabrication facility at Springfields, and the low level waste disposal facility at Drigg. Also presented are "reference facilities". These are suitably selected facilities which are not within the UK, but are still part of the nuclear fuel chain. Thus, for the extraction stage, UK power plants obtain their fuel from a number of mines. It would clearly be impractical to evaluate risks from each one, so a "reference" mine was chosen that is assumed to be operational over the 2010 – 2070 period under study. A real mine may not have an operational lifetime as long as this, but for the purposes of using reference facilities it is assumed that, if one mine were to cease operation, uranium would be imported from another mine with similar characteristics. A risk factor is also assigned for the construction of uranium mines, which is conservatively assumed to occur continuously throughout the lifetime of the mine. Mine construction can occur concomitantly with operation, as both processes require the extraction of underground material. However, it is unlikely that construction would occur over the whole operating period of the mine. The scale of mine construction is assumed to be linearly dependent on the scale of new power plants built, so that when the risks of mine construction are normalised against the total amount of energy generated, the risks are approximately independent of the time period assumed for construction. Mine decommissioning was also assumed to occur continuously over this period. The main risks at this stage are occupational immediate fatality risks. The available fatality data used for these risks only give indications for those fatalities that occurred during operation, and those that did not. In the interests of conservatism, the data for non-operational fatalities are ascribed to the construction stage. This means that the decommissioning stage has no significant risks associated with it. The characteristics of the reference mine are based on data observed at various mines throughout the world, in order to give a representative sample.

A similar process was carried out for reference preparation facilities. Construction risks for reference preparation facilities were not included in the analysis as the number of new preparation facilities that may get built is independent of the scale of new UK nuclear power plants. This is because these facilities are already in place and operational, meaning that it is unlikely that any new facilities would need to be constructed. The risks from the operation of the UK preparation facilities at Capenhurst and Springfields are accounted for within the reference facilities, although the decommissioning risks of these facilities are included separately. The reprocessing risks are taken as arising from Sellafield in the UK, in which operational processes and decommissioning processes are currently taking place. The reference waste disposal facilities are the LLW/ILW repository and HLW/Spent Fuel repository currently being planned by the NDA. These are assumed to be constructed simultaneously over the period 2020-2040. In addition, the currently operational low level waste repository at Drigg is also assessed, which is assumed to operate until 2071, although as with Sellafield, decommissioning activities are also taking place simultaneously.

Table 44 provides data for lifetimes for the construction, operation and decommissioning of each UK power plant and other facilities over the assessed period from 2010 to 2070, as well as the capacities and capacity factors (the capacity factor, which is also frequently known as the load factor, is the ratio of the actual amount of energy generated within a given year to the capacity of the plant). Also shown is the calculated remaining output of the operational plants over the 60 year period, which is the operational lifetime (to 2070) multiplied by the capacity and the capacity factor. Over the period 2010 – 2070, there will be approximately 84.1 GWa of electricity generated from existing nuclear power plants. This figure will be important in the calculation of current and incremental impacts. The data sources are also provided in the accompanying notes. Much of the data was obtained from the World Nuclear Association, which provides a very comprehensive and publicly available reactor database, see [207]. The datum shown for Dounreay are for both plants that generated electricity over the period 1962 to 1994. Where data was not available, it was assumed that decommissioning lifetime was 100 years. Lifetime capacity factors are shown for plants undergoing decommissioning, whilst latest year capacity factors were used for currently operational power plants, with the exception of Hartlepool power station, where the only available datum was for lifetime output.

Table 45 shows the assumptions used regarding new nuclear build. Two plants are assessed – the EPR and the AP1000. The EPR is assumed to require 5 years to construct, whence it will operate for 60 years, and require 100 years to decommission. The capacity of an EPR is taken as 1.65 GW, and is assumed to have a capacity factor of 90%. The AP1000 is assumed to require 4 years for construction, 60 years for operation, and 100 years for decommissioning. The capacity of an AP1000 is assumed to be 1.12 GW, and the capacity factor is taken as 93%. Again, data sources are provided in the accompanying notes to each table.

15.3 Extraction

Mining has historically been a very dangerous activity. Around 800 people were killed annually in UK coal mines around 60 years ago. However, substantial safety improvements have occurred, both in the UK and globally, so that mining is now much safer and fatalities are increasingly rare. As noted above, uranium is imported from many countries around the world, with the world's largest producers being Kazakhstan, Canada, Australia and Namibia. Occupational fatality data was obtained for the two uranium mines in Namibia: Rossing and Langer Heinrich; the Olympic Dam mine in Australia; and data for all uranium mines operated by Areva. These are shown in Table 49, with the accompanying notes providing the calculations and references. These sources represent the majority of uranium imported into the UK by British Energy, see British Energy/AEA Energy (2009) [25]. The exposure rates are presented in terms of the number of fatalities per GWa, where it is assumed that 154 tonnes of extracted uranium oxide is required to generate one GWa of electrical energy. This figure includes reprocessing of fuel for re-use in generation. From this table, it can be seen that all sources provide comparable risks. The lowest exposure rate comes from the Olympic Dam mine in Australia, where there are 1.6×10^{-4} fatalities/GWa. The highest exposure rate occurs in the Namibian mines, where there are 7.3×10^{-3} fatalities/GWa. The Areva data is almost exactly halfway between these two, at 3.4×10^{-3} fatalities/GWa. The high and low estimates used for immediate occupational impacts involved with uranium mining is therefore $1.6\times10^{-4} – 7.3\times10^{-3}$ fatalities/GWa.

It is assumed that all the fatalities shown in Table 49 occurred during operation of the mine. In order to estimate the exposure rate for the construction process, it is assumed that the ratio between the construction and operation exposure rate for uranium mining is equal to that observed for coal mining in the UK. As will be discussed in section 16.3, the fatalities due to non-operational coal mining activities were 37.5% of the operational fatalities over the period 2005/06 to 2009/10. Therefore this factor will be applied to the operational fatalities in uranium mining to determine the construction exposure rate. The high and low values are therefore 2.7×10^{-3} and 6.1×10^{-5} fatalities/GWa respectively. Since the construction impacts are assumed to be dependent upon the scale of new nuclear build, these impacts are scaled against the amount of electricity generated by new build stations as a fraction of the total amount of electricity generated over the assessed period. These risks then contribute to the "incremental" risks discussed in section 13.1. The baseline situation is when there are no new nuclear plants built. The impacts calculated from this scenario are the "current" impacts. The construction risks arising from the extraction phase do not contribute to the current impacts as they are dependent upon scale of new build only. Thus, building new plants adds risk to the overall system, and this additional risk contributes to the incremental impacts.

The exposure rates given above then allow the loss of life expectancy and hazard elimination premium (HEP) to be computed. The loss of life expectancy is determined for a long exposure lasting 60 years, which is the assumed lifetime of the reference mine, and is also the assumed time over which construction activities take place. This loss of life expectancy is then converted into a HEP, in £/GWa, using equation (13.6). For operational impacts, this HEP is equal to the current impact and the incremental impact, as the HEP is assumed to scale linearly with the total output from existing and new power stations. For construction impacts, the current impact is zero, while the incremental impact is calculated relative to the amount of electricity generated from new build plants.

Another source of risk arising at the extraction stage is from radiation exposure which results in occupational delayed impacts and public delayed impacts. Data is available on average dose to staff from British Energy/AEA Energy (2009) [25], which gives high and low average doses as 5 and 3.1 mSv/a experienced by staff in Namibia's Rossing mine and Australia's Ranger mine respectively. Collective dose can be determined from staff estimates. The Rossing mine had an average staff size of 1,993 between 2005 and 2009, see Chamber of Mines Namibia (2009) [30]. For simplicity, all staff will be assumed to be employed in operational activities, so that this impact only needs estimating for the operation stage of mining. Using this staff figure, the annual collective dose is 6.2 – 10.0 man-Sv/a. This data is shown in Table 52. The loss of life expectancy and HEP can then be calculated over the 60 year operational period. The delayed public impacts estimated from Ball et al (1994) [15], which gives the collective dose to a typical regional population from a model uranium mine as 29 man-Sv over a 20 year lifetime. The annual public dose to the regional population is therefore 1.45 man-Sv/a. However, it is also possible to compute data for collective doses to other regions. In section 13.4 it was explained that radioactive emissions can become globally circulated and potentially result in exposures to a very large number of people, although the dose received by such exposures is small. Three regions can be defined over which collective dose impacts are assessed – the UK, Europe and the world. A problem with dose emissions from uranium mines is that they are not situated in the UK. An accurate analysis of these impacts would use mortality statistics specific to the actual regional population near the mine. Notwithstanding this, using UK statistics as a proxy for regional populations will allow impacts to be estimated. The same issue applies to using the European region, which will usually not be the continent in which the mine is located. To estimate the collective dose to the European and world region, a multiplier is calculated from Table 51, which gives predicted collective doses to the UK, European and world populations from the new PWR power stations. The collective dose to the European population is on average 8.77 times the UK collective dose, while the world collective dose is on average 80.24 times the UK collective dose. It is therefore assumed that these multipliers apply to the collective dose resulting from radionuclide emissions from the reference uranium mine. Therefore, the collective dose to the European region is 12.72 man-Sv, and the collective dose to the world region is 116.4 man-Sv. The sensitivity of the results to the assumptions regarding these collective dose regions is discussed in chapter 19. Another feature assessed is sensitivity to the use of cut-off doses. These are effective thresholds, so that doses below these cut-offs are not assessed. These were explained in section 13.4 as allowing more reasonable calculations of collective dose emissions, as trivial doses can be disregarded. The public doses are shown in Table 53. This data is sufficient to calculate the loss of life expectancy to members of the public, and the associated HEP.

There are no public pollution impacts associated with uranium mining, owing to negligible particulate matter emissions. It has also been assumed that the impacts from occupational lung disease and major accidents are negligible. Although these risks are concerns for uranium miners, they are small when normalised against the amount of electrical energy equivalent extracted from the mines.

15.4 Preparation

The preparation stage of the fuel chain involves conversion, fabrication and enrichment activities. The baseline scenario from which the current risks are calculated assume that there will be no new facilities constructed, as they are already in place – either in the UK or abroad. Although the UK currently has the facilities required to carry out all of the preparation activities, they are all scheduled to cease operation over the period under study. At present, there have been no plans discussed for life extension or replacement. If the facilities are not extended or replaced, then it would be the case that all preparation activities would occur outside of the UK. Hence, occupational fatality data from Areva, which operates many such facilities, were used for the reference facilities. This is also a conservative estimate, as there have not been any fatalities reported in the UK preparation facilities. There have been four fatalities in all of Areva's "Front End" operations over the period 2004 – 2008. These include mining, conversion, fabrication and enrichment activities. The 95% confidence limits for a count of four are 1.1 – 10.2, which are used to estimate the high and low values of the impacts at the preparation stage. The fatalities are apportioned according to the number of staff in each area, which is given in Table 46, and the results of the apportioning are shown in Table 47. In order to arrive at an exposure rate in terms of the number of fatalities per GWa, the fatalities were divided by Areva's share of the global market, to produce an estimate of the global number of fatalities in the preparation stage. These are shown in Table 48. In 2009, there was approximately 292 GWa of electricity generated by nuclear power globally. The exposure rates are then given in Table 50. Immediate occupational decommissioning risks of the UK facilities are included in the analysis. These risks were assumed to be the same as the decommissioning risks of power plants, which were found to be small, as will be described in more detail in section 15.5.

Other impacts at the preparation stage are radiation doses to workers and to the public. For occupational dose, the average annual dose to workers was found to range from 0.13 – 0.403 mSv/a see British Energy/AEA Energy (2009) [25]. These figures can then be used as the high and low estimates. The average staff number working in preparation activities for Areva over 2005 – 2009 was then used to estimate the collective dose. To estimate the dose at the Capenhurst and Springfields sites, data from the NDA was used. Further details can be found in the notes to Table 52. The only public dose data was for the Springfields facility, from which arise public exposures of 0.41 man-Sv (UK population) see Ball et al (1994) [15]. The public exposures at the other facilities are assumed to result in similar exposures. Again there are no pollution impacts associated with this stage.

15.5 Generation

The generation of electricity by nuclear power involves immediate occupational risks and delayed occupational and delayed public risks resulting from radiation. There is also the risk of a major nuclear accident occurring causing large loss of life and environmental damage. There are currently ten operational nuclear plants in the UK. There are also a further twelve which are undergoing decommissioning. The present value of the risks resulting from these activities over the 2010 to 2070 period is used to calculate the current impacts for the nuclear generation stage. To calculate the incremental risks, it is assumed that a number of new nuclear plants will be built.

The new plants will be an equal mixture of EPRs and AP1000s which are assumed to commence construction in 2012. The EPRs are assumed to require five years to construct, while the AP1000s are assumed to require four. In addition it is assumed that EPRs can be constructed at a rate of one every two years, while the AP1000 can be constructed at a rate of one per year. This is because the AP1000 is simpler and more modular in its design, although it has a smaller capacity than the EPR. Both plants are assumed to have an operational lifetime of 60 years. Thus, any decommissioning of new build plants will occur after 2070 and so the impacts will not be assessed. These assumptions may be changed to give different assumed scenarios. However, the overall results are not greatly affected by them, as the impacts are linear with new build output, and so when normalised against this output, remain fairly constant.

There have not been any nuclear plants constructed in the UK since Sizewell B, which was completed in 1994. It is therefore impossible to directly estimate the fatality risk of constructing new power plants. It is however possible to estimate this risk indirectly. Ball et al (1994) [15] reported that the fatality rate resulting from the construction of Sizewell B was broadly consistent with the fatality rate estimated from national statistics for the entire construction industry. Thus, the current fatality rate for the UK construction industry, as provided by the Health and Safety Executive (HSE) [105], will be used to estimate the construction risks for new nuclear build. Over the period 2005/06 to 2009/10, there were 212 fatalities in the construction industry, and the per person fatality rate was 3.5×10^{-5} (95% C.L: 1.7 – 5.3×10^{-5}). This figure is converted into the exposure rate per GWa by multiplying this figure by the number of man-years required for construction, and dividing by the lifetime output of the plant. The number of man-years required is estimated to be 5,420, based on an average workforce of 1,084 working for 5 years, see Cogent (2009) [33]. The lifetime output is calculated based on EPR data from Table 45, which gives a lifetime output of 89 GWa. Using these figures, the exposure rate for plant construction is calculated as 2.1×10^{-3} (95% C.L: 1.0 – 3.2×10^{-3}) fatalities per GWa.

The operation hazard rate is estimated from the number of nuclear plant fatalities recorded over the past five years. Table 86 and Table 87 in the Appendix D detail all recorded deaths and the electricity generated by each technology over this period. The table shows that there has been one nuclear fatality and 36.4 GWa of nuclear electricity supplied, giving an exposure rate of 2.8×10^{-2} fatalities per GWa. The 95% confidence limits for a Poisson random variable with a count of one, are 0.03 – 5.6, so that the exposure rate is 7×10^{-4} – 0.15 fatalities/GWa.

There were no fatalities associated with decommissioning over this period. It will therefore be assumed that the lower bound of the exposure rate is zero. To estimate the upper bound, Poisson statistics may again be used. For a count of zero, the upper 95% confidence limit is 3.7. Care must be used with such statistics that the risks are not grossly overestimated, as a zero count may have occurred because there is no risk, rather than due to chance. However, extensive decommissioning activities have occurred over the period, and the activities themselves are similar to construction, except that they occur in reverse, and at a much slower rate. It would therefore seem normal to expect fatalities to occur from this process. Using the upper limit for the Poisson statistic, the high exposure rate is 4.5×10^{-2} fatalities/GWa. However, this figure is more than an order of magnitude greater than the exposure rate for the construction stage. It does not seem credible that the process of decommissioning contributes more than ten times the number of fatalities than the initial construction process does. This problem highlights the difficulty with using Poisson statistics for zero counts. Because this upper limit is not judged to be credible, the upper limit for construction is instead used. Thus, the exposure rate for decommissioning is 0 – 3.2×10^{-3} fatalities/GWa.

The occupational exposures to radiation occur at both the operation and decommissioning stage. For plants undergoing decommissioning, data on exposures and staff size is taken from the NDA (2011a, b) [138] [139]. The staff size is estimated from the "Lifetime Plan" (LTP), which is a document published by the NDA that details the decommissioning activities that will take place over the allocated time. These LTPs also provide a full-time equivalent staff curve, from which the average number of staff over the period 2010-2070 can be estimated. The data is shown in Table 52. To estimate the average dose and staff size at the currently operational power plants, staff size data is taken from Cogent (2009) [33], while operational doses were taken from British Energy (2009) [23]. To estimate the dose received from decommissioning a figure from Ball et al (1998) [15] of 12.2 man-Sv is given for decommissioning a typical PWR. It will be assumed that this figure is evenly distributed over 100 years, a typical decommissioning period. It will also be assumed that this figure applies to the AGR's that will undergo decommissioning, as well as the PWR at Sizewell. The dose from decommissioning the two Magnox plants at Oldbury and Wylfa is estimated by averaging the collective dose from all other Magnox plants currently undergoing decommissioning. Again, see Table 52 for more details.

Data for radiation doses to the public from nuclear power plants can be estimated from a research document by Harvey et al (2008) [92]. This document gives the collective dose to the public arising from each nuclear power plant in the UK. Data is available for the years 1997, 1999, 2002 and 2004, and are presented as doses to the European population estimated over a 500 year period. The UK collective dose can be estimated by dividing by the multiplier of 8.77 derived in section 15.3. Although summing the dose over a 500 year period is not the preferred method of estimating collective dose (and is now contrary to ICRP recommendations see ICRP (2007) [113]), attempting to modify this figure would likely lead to pessimistic conclusions, and so will not be done. However, this dose will be assessed for sensitivity inchapter 19 by using cut-off doses.

The radiological impacts resulting from new build plants may also be assessed. The pre-construction safety reports of both the EPR and AP1000 give the predicted collective dose to staff see AREVA/EDF (2011) [10], and Westinghouse (2010c) [204], while the pre-construction environmental reports give the predicted public collective dose. The data for these doses are given in Table 51, Table 52, and Table 53.

The final impact that needs estimating in the generation stage is the risk of a major nuclear accident. To estimate this impact, data was obtained from Westinghouse's probabilistic risk analysis of its AP1000 reactor, see Westinghouse (2010b) [203]. The frequencies and resulting doses of a range of different release scenarios is presented in Table 54. Table 55 then presents the calculation of the loss of life expectancy resulting from the impact. A large nuclear accident is assumed to immediately kill 20 workers who receive massive doses of 10 Sv each. Another 100 workers then will receive a dose of about 0.56 Sv each. The remaining collective dose of about 68,000 Sv is then to the public, none of whom are assumed to receive a dose large enough to instantly kill them. A large nuclear accident also results in environmental damage which will incur financial remediation costs, assumed to be paid by the operator. Again, the data is taken from the AP1000 probabilistic risk analysis. This indicates that a large radioactive release will result in environmental costs of £20 billion. A core damage event, which does not result in large environmental releases but still causes substantial damage to the plant, will incur environmental costs of £2 billion. The respective frequencies of these two events are 6×10^{-8} and 5.1×10^{-7} respectively. The risk multipliers for these events were both found to be very close to unity, and so $m_{r.max}$ = 1 was used to assess the financial HEP. Normalising against the amount of electricity generated, this is then £2,100 /GWa. The abnormal risks were assumed to apply to the new build plants and the currently operational PWR and AGRs.

15.6 Reprocessing

In estimating the risks posed by the reprocessing stage of the nuclear fuel chain, data from Sellafield is used. Sellafield is a complex facility that deals with nuclear waste from all over the world. Much of the activities currently being carried out at Sellafield involve preparations for passivation, in which major hazards and environmental risks are reduced. Some activities have also begun on the decommissioning of some waste treatment plants, although a number of such plants will still be operating for some time. Data on these activities is available from the Sellafield LTP available from the NDA (2011a) [138]. Over the period 2010 – 2070, three quarters of the scheduled activities will be for decommissioning related activities, whilst the remaining quarter is for operational activities. The staff size can be estimated from the LTP over this period, and is split between operational and decommissioning procedures in this proportion. It is taken that no further reprocessing facilities will be constructed over the period of assessment.

There have been no recent fatalities reported at Sellafield. To estimate immediate occupational fatality impacts, it will be assumed that the major risk arises from the decommissioning activities. It will also be assumed that the decommissioning risks can be estimated from the construction risks. This is because, as has already been discussed earlier, these processes are similar. Fatality data is available for the construction of the Thermal Oxide Reprocessing Plant (THORP), which began operating in 1997, and is due to be decommissioned over the assessed time period. Ball et al (1998) [15] discuss that there were two fatalities in the construction of THORP, and the expected energy equivalent lifetime throughput is 400 GWa. The exposure rate is therefore 0.005 fatalities/GWa. The 95% confidence limits are 6×10^{-4} – 0.018 fatalities/GWa. The other way of estimating the exposure rate would be to assume that the no observed fatalities over the recent five year period occurred by chance, and use Poisson statistics with a count of zero, which gives an upper confidence limit as 3.7 If the lifetime of THORP is taken as twenty years, then the throughput over the most recent five years was 100 GWa. The exposure rate therefore ranges from 0 – 0.037 fatalities/GWa. Both of these estimates are clearly similar. The initial estimate based on the construction fatality rate will be used in calculating the impact.

The occupational radiological impact resulting from Sellafield is taken from British Energy's estimate, see British Energy/AEA Energy (2009) [25]. The public radiological impact is calculated from the same reference as used for the power plants. The data is shown in Table 52 and Table 53.

15.7 Waste Storage and Disposal

The reference waste facilities are the low-level waste repository (LLWR) based at Drigg and two further repositories for more radioactive waste, which are assumed to be constructed between 2020 and 2040, see DECC (2011i) [56]. There is currently scheduled to be more construction work undertaken at Drigg, to accommodate more low level waste, as well as normal operational work and some minor decommissioning work. It will be assumed that the main source of immediate occupational fatality risk arises from the construction activities at the LLWR. Thus, the construction risks for all three waste facilities need to be evaluated. Since the waste facility at Drigg is above ground, it will be assumed that the construction work carried out there will have similar risks to those in the quarrying industry. These are given in chapter 14, in Table 22 and Table 25, which show that there have been ten fatalities over the most recent five years, and that 1,275 Mt of stone has been quarried. The exposure rate is then 0.004 – 0.014 fatalities/Mt. The volume of low level waste produced by an EPR is about 427 m^3/GWa [8]. Assuming that the density of waste is 2 tonnes/m^3 [15], the exposure rate can then be re-expressed as $0.3 – 1.2\times10^{-5}$ fatalities/GWa.

The other repositories are to be built deep underground, and so it is assumed that the risks for this project are similar to the risks of coal mining provided by Table 22 and Table 26, from which the exposure rate of 0.07 – 0.24 fatalities/Mt can be calculated. One of the repositories will contain both low-level waste (LLW) and intermediate-level waste (ILW). An EPR will produce around 136 m^3/GWa of ILW. Taking an average of the LLW and ILW volumes, and assuming the same density allows the exposure rate to be expressed as $4.0 – 14\times10^{-5}$ fatalities/GWa. The other repository will contain high level waste (HLW) only. The volume of HLW produced by an EPR is 12.4 m^3/GWa. The associated exposure rate is $0.2 – 0.6\times10^{-5}$ fatalities/GWa.

The average occupational dose and staff size for the LLWR is available from the NDA (2011a, b) [138], [139]. The staff size is apportioned according to the amount of construction, operation and decommissioning activities scheduled to take place over the 2010 – 2070 period. This results in a construction staff size of 18, an operational staff size of 61 and a decommissioning staff size of 27. It will be assumed that all occupational dose is to the operational staff, as discussed in Ball et al (1998) [15]. The collective occupational dose at the LLWR is then 0.02 man-Sv. The occupational dose at the LLW/ILW and the HLW is estimated from Nirex, now part of the NDA, see Nirex (2005) [140], who estimate that the maximum realistic occupational dose for both repositories would be less than 10% of the 20 mSv/a regulatory limit. The upper limit will therefore be assumed to be 2 mSv/a, and the lower limit will be taken as zero. The public dose resulting from the LLWR and the two new repositories is expected to be negligible, even summing over global exposures for 10,000 years, see Ball et al (1994) [15].

15.8 Materials

Three stages of the nuclear fuel chain are assumed to have new facilities constructed under the scenario of nuclear expansion – the extraction stage, the generation stage and the waste disposal stage. The preparation and reprocessing stage already have facilities in place that are sufficient to perform the necessary tasks should the nuclear power industry expand. It is therefore necessary to estimate the quantity of material required per unit of electrical energy for a typical uranium mine, a new build PWR reactor, and the proposed LLW/ILW and HLW repositories. The risk factors derived for the materials in chapter 14 can then be applied. It was discussed in that chapter that, in order to simplify the analysis, only materials used in massive quantities will be analysed. A threshold of 10^{-4} Mt/GWa was taken as defining the level above which, material requirements are defined as "massive". Material quantities per GWa are given in Table 56. For mines and power plants, the only materials used in massive quantities are steel and concrete. For waste repositories, only aggregates are required in massive quantities. The risk factors per Mt are given in Table 34 for aggregates, while for steel and concrete they are given in Table 36 and Table 37 respectively. These can then be used to calculate the risks associated with material requirements specific to the nuclear industry. Only the material risks classed as "post-decommissioning" in the above tables contribute to current impacts. The risks classed as "pre-construction" contribute to the incremental impacts.

15.9 Transportation

The risk factors per Mt of transporting construction materials and the raw materials required to make them, have already been evaluated in chapter 14. These can be converted into a risk factor per GWa by multiplying by the appropriate factor in Table 56. The impacts are assessed for transportation of materials from the quarry/mine to the manufacturing plant, from the manufacturing plant to the uranium mine/power plant/waste repository, and finally to the waste disposal facility/recycling plant. Although the uranium mine will be constructed abroad, UK transport risk factors will still be used. Clearly, the indigenous transport risks may be very different to UK risks, so that caution must be used when viewing these figures. The transportation of the uranium fuel is also included. It is assumed that the uranium is transported 150km from the port to the preparation facilities, 200km from the preparation facilities to the power plant, another 200km from the power plant to the reprocessing site, and finally 50km from the reprocessing site to the waste disposal site – a total distance of 600km. The mode of transport is assumed to be 30% by road and 70% by rail, as is normally used. All transportation from the power plant to the waste disposal/recycling facility contributes to the current risks, while all transport up to the power plant contribute to the incremental risks.

15.10 Summary and Discussion

Table 57 and Table 58 present the hazard elimination premiums (HEP), in terms of million pounds per Gigawatt-year (£M/GWa), for all impacts at each stage of the nuclear fuel chain, for current and incremental impacts.

The results show that, for current impacts, the major immediate fatality risks occur to workers at nuclear power plants and at the reprocessing facility. The major delayed impacts are to the public from pollution emissions in the construction materials chain, and to workers at the reprocessing facility. Immediate occupational fatalities contribute the largest impact, and this is followed by delayed public fatalities and delayed occupational fatalities. Immediate public fatalities and abnormal impacts contribute some of the lowest risks. The stage of the fuel chain which contributes the least impacts is the waste disposal and storage stage, whilst the stage with the greatest impacts is the generation stage. When taken together, immediate and delayed risks contribute similar amounts to the overall impacts. This is also true of occupational and public impacts.

For incremental impacts, the largest risk again arises from immediate fatality impacts to power plant workers. Following this are immediate fatality risks to workers at the preparation facilities. Again, immediate public fatalities and abnormal impacts contribute low risks, and the greatest risks arise at the generation stage. When taken together, occupational immediate impacts, occupational delayed impacts and public delayed impacts are all comparable. Total occupational risks are somewhat greater than total public risks, and total immediate fatalities are greater than the total delayed fatality impacts. The incremental impacts are also generally smaller than the current impacts, except for immediate public fatalities and abnormal fatalities. This means that adding new power plants to the UK nuclear energy system will result in risks that are smaller than those that are already experienced.

The delayed public fatalities are sensitive to the collective dose assumptions used. Chapter 19 will assess how the results change when different regions are used to estimate the collective dose. Also assessed are the effects of introducing cut-off doses, and the effect of using coal mining safety statistics of the countries that the UK import the majority of its coal from.

Abnormal risks, which arise from possible large scale nuclear accidents, and were calculated from Westinghouse's probabilistic risk analysis of its new AP1000 reactor (see Westinghouse (2010b)) [203], are low, although these risks may be of particular importance to the social acceptability of nuclear power generation. The effects of the earthquake and tsunami in March 2011 on the Japanese Fukushima Daiichi BWRs demonstrated the possibility of multiple incidents occurring on large sites, and causing massive damage, although the long-term global impact of the radiation release is likely to be relatively low. Generally, however, the possible, large effects of such an accident should be balanced by the very low probability of such an event occurring. It is again emphasised that the analysis refers to current new reactor designs rather than to older designs such as those affected in Japan.

UK Nuclear Plants	Type	Status	Construction[a]	Operation[a]	Decommissioning[b]
Calder Hall	Magnox	Decommissioning	1953-1958	1956-2003	2003-2117
Dounreay	FBR	Decommissioning	1955-1975	1962-1994	1977-2333
Chapelcross	Magnox	Decommissioning	1955-1959	1959-2004	2004-2128
Berkeley	Magnox	Decommissioning	1957-1962	1962-1989	1989-2083
Bradwell	Magnox	Decommissioning	1957-1962	1962-2002	2003-2104
Windscale	AGR	Decommissioning	1958-1962	1963-1981	1982-2065
Hunterston A	Magnox	Decommissioning	1957-1964	1964-1990	1993-2090
Hinkley Point A	Magnox	Decommissioning	1957-1965	1965-1999	2000-2104
Dungeness A	Magnox	Decommissioning	1960-1965	1965-2006	2008-2111
Trawsfynydd	Magnox	Decommissioning	1959-1965	1965-1991	1993-2098
Sizewell A	Magnox	Decommissioning	1961-1966	1966-2006	2007-2110
Winfrith	SGHWR	Decommissioning	1963-1967	1968-1990	1991-2019
Oldbury	Magnox	Operation	1962-1968	1967-2011[c]	2011-2101
Wylfa	Magnox	Operation	1963-1971	1971-2011[c]	2011-2125
Hunterston B[e]	AGR	Operation	1967-1976	1977-2016	2016-2116
Hinkley Point B[e]	AGR	Operation	1967-1975	1976-2016	2016-2116
Hartlepool[e]	AGR	Operation	1968-1984	1985-2019[d]	2019-2119
Dungeness B[e]	AGR	Operation	1965-1983	1986-2018	2018-2118
Heysham 1[e]	AGR	Operation	1970-1983	1983-2019[d]	2019-2119
Heysham 2[e]	AGR	Operation	1979-1988	1988-2023	2023-2123
Torness[e]	AGR	Operation	1980-1988	1989-2023	2023-2123
Sizewell B[e]	PWR	Operation	1988-1994	1995-2035	2035-2135
Other Facilities					
Capenhurst[a]	Enrichment	Decommissioning	1952-1961	1961-1982	1982-2120
URENCO UK	Enrichment	Operation	N/A	1961[b]-2035[g]	2035-2135
Springfields[a]	Fabrication	Operation	N/A	1946-2023	2023-2031
Sellafield[a]	Reprocessing	Reference	N/A	1947-2086	2006-2105
Drigg LLWR[h]	Disposal	Operation	1956-2066	1959-2071	2008-2080
Reference Facilities					
Mine	Mining and Milling	Reference	2010-2070	2010-2070	2010-2070
Preparation Facilities	Conversion, Enrichment, Fabrication	Reference	N/A	2010-2070	N/A
LLW/ILW GDA[i]	Disposal	Reference	2020-2040	2040-2090	N/A
HLW/SF GDA[i]	Disposal	Reference	2020-2040	2040-2090	N/A

Table 43 Construction, operation and decommissioning dates of UK nuclear facilities, including assumed dates for reference facilities.

a. [207], unless indicated.
b. [138], unless indicated.
c. [210]
d. [211]
e. No data was found for decommissioning dates, assumed decommissioning lifetime of 100 years.
f. [138]
g. [100]
h. [131]
i. [56]

UK Nuclear Plants	Remaining Lifetime from 2010 to 2070			Net Capacity (GW)[a]	Capacity Factor[a]	Output Remaining from 2010 (GWa)
	Const-ruction	Operation	Decomm-issioning			
Calder Hall	-	-	60	0.20	0.83	-
Dounreay	-	-	60	0.26	0.24	-
Chapelcross	-	-	60	0.20	0.92	-
Berkeley	-	-	60	0.28	0.61	-
Bradwell	-	-	60	0.25	0.66	-
Windscale	-	-	55	0.03	0.31	-
Hunterston A	-	-	60	0.32	0.82	-
Hinkley Point A	-	-	60	0.47	0.72	-
Dungeness A	-	-	60	0.45	0.74	-
Trawsfynydd	-	-	60	0.39	0.75	-
Sizewell A	-	-	60	0.42	0.73	-
Winfrith	-	-	9	0.09	0.52	-
Oldbury	-	1	59	0.43	0.55	0.24
Wylfa	-	1	59	0.98	0.65	0.64
Hunterston B	-	6	54	1.19	0.81	5.80
Hinkley Point B	-	6	54	1.22	0.73	5.36
Hartlepool	-	9	51	1.21	0.68	7.41
Dungeness B	-	8	52	1.11	0.44	3.91
Heysham 1	-	9	51	1.15	0.69	7.10
Heysham 2	-	13	47	1.25	0.79	12.88
Torness	-	13	47	1.25	0.91	14.78
Sizewell B	-	25	35	1.19	0.87	25.95
Other Facilities						
Capenhurst	-	-	60	N/A	N/A	N/A
URENCO UK	-	25	35	N/A	N/A	N/A
Springfields	-	13	8	N/A	N/A	N/A
Sellafield	-	60	60	N/A	N/A	N/A
Drigg LLWR	56	60	60	N/A	N/A	N/A
Reference Facilities						
Mine	60	60	60	N/A	N/A	N/A
Preparation Facilities	60	60	0	N/A	N/A	N/A
LLW/ILW GDA	20	30	0	N/A	N/A	N/A
HLW/SF GDA	20	30	0	N/A	N/A	N/A

Table 44 Lifetimes, capacities and capacity factors and remaining output of UK nuclear facilities from 2010 to 2070. Total output remaining from existing nuclear plants is 84.1 GWa.

a. [207]. For plants undergoing decommissioning, the lifetime generation data has been used to calculate the capacity factor. For currently operational plants, the most recent available data has been used.

			Lifetimes (year)			Net Capacity (GW)	Capacity Factor
New Build	**Type**	**Status**	**Const-ruction**	**Operation**	**Decomm-issioning**		
GDA[a]	EPR	Reference	5	60	100	1.65	0.9
GDA[b]	AP1000	Reference	4	60	100	1.117	0.93

Table 45 Assumptions used for new nuclear plants.

a. [11]

b. [204]

Areva Employment Data	2009	2008	2007	2006	2005	2004	Total (%)
Mining	5,129	4,602	3,525	2,993	2,657	2,390	16,167 (27%)
Conversion	1,630	1,666	1,630	1,601	1,640	1,652	8,189 (13%)
Enrichment	2,598	2,458	2,095	1,902	1,498	1,517	9,470 (16%)
Fabrication	5,155	5,256	5,083	5,245	5,252	5,393	26,229 (43%)
All "Front End" Staff	14,763	14,240	12,577	11,995	11,047	10,952	10,952

Table 46 Areva employment figures, 2004 – 2009. From [3], [4], [5], [6].

Areva Fatality Data	2009	2008	2007	2006	2005	2004	Annual Average
All "Front End" Fatalities	N/A	1	0	1	1	1	0.8
Apportioned to Mining							0.21
Apportioned to Conversion							0.11
Apportioned to Enrichment							0.12
Apportioned to Fabrication							0.35

Table 47 Areva fatality figures, 2004 – 2009. From [3], [4], [5], [6].

	Areva Global Market Share 2009 (%)	Inferred Global Average Fatalities
Mining	19.0	1.12
Conversion	20.5	0.53
Enrichment	22.0	0.57
Fabrication	35.0	0.99

Table 48 Areva global market share and inferred global average fatalities

Uranium Mines	Annual Fatalities	Annual Output (Tonnes)	Annual Output (GWa)[a]	Fatalities/ GWa
Namibia[b]	0.20	4227	27.4	0.0073
Olympic Dam	0.004[c]	4007[d]	26.0	0.0002
Areva	1.12[e]	50772[f]	330	0.0034

Table 49 Uranium mines output, safety data and exposure rates.

a. Here assumed 200 tonnes of uranium is needed to produce 1 GWa of initial electricity, as in [15]. Also assumed that 30% of used fuel can be reprocessed and used in further electricity generation [209]. Therefore 200 tonnes can be used to produce 1.3 GWa of electrical energy. Therefore 154 tonnes are required per GWa of electricity produced.
b. [30]. Data is over period 2005 – 2009.
c. [18] gives annual fatalities for all BHP Billiton employees. This is then apportioned thus: shows that staff at the Olympic Dam mine constitute 3% of all BHP employees [19], and the uranium from the Olympic Dam mine represents 2% of Olympic Dam's production[d], so that the annual fatalities ascribed to uranium mining in Olympic Dam is 0.07% of the annual total. Data was only available for 2007.
d. [17]
e. See Table 47 and Table 48
f. [208] Figure is global uranium output.

Preparation Stage	Fatalities/GWa (95% Confidence Limits)
Conversion	$1.8\ (0.5 – 4.6) \times 10^{-3}$
Enrichment	$1.9\ (0.5 – 5.0) \times 10^{-3}$
Fabrication	$3.4\ (0.9 – 8.7) \times 10^{-3}$
Total	$7.1\ (1.9 – 18) \times 10^{-3}$

Table 50 Exposure rates at the preparation stage.

Collective Dose (man-Sv)	EPR[a]			AP1000[b]		
	UK	Europe	World	UK	Europe	World
Atmospheric	0.09	1.11	15.8	0.25	1.90	12
Liquid	0.02	0.15	1.1	8.3×10^{-4}	3.8×10^{-3}	5.4×10^{-2}
Total	0.11	1.26	16.9	0.25	1.90	12.1

Table 51 Predicted collective doses arising from emissions of radionuclides for the EPR and AP1000 new PWR reactors.

a. [9]
b. [202]

UK Nuclear Plants	Average No. of Workers[a]		Average Annual Collective Dose (man-Sv)[a]	
	Operation	Decomm-issioning	Operation	Decomm-issioning
Calder Hall	-	27	-	0.02
Dounreay	-	365	-	0.02
Chapelcross	-	67	-	0.01
Berkeley	-	28	-	0.001
Bradwell	-	47	-	0.01
Windscale	-	108	-	0.03
Hunterston A	-	34	-	0.001
Hinkley Point A	-	48	-	0.01
Dungeness A	-	69	-	0.002
Trawsfynydd	-	30	-	0.001
Sizewell A	-	25	-	0.001
Winfrith	-	270	-	0.03
Oldbury	850	93	0.16	0.005
Wylfa	764	63	0.14	0.005
Hunterston B	554[b]	63[c]	0.05[j]	0.12[k]
Hinkley Point B	554[b]	63[c]	0.09[j]	0.12[k]
Hartlepool	554[b]	63[c]	0.09[j]	0.12[k]
Dungeness B	554[b]	63[c]	0.09[j]	0.12[k]
Heysham 1	554[b]	63[c]	0.09[j]	0.12[k]
Heysham 2	554[b]	63[c]	0.09[j]	0.12[k]
Torness	554[b]	63[c]	0.09[j]	0.12[k]
Sizewell B	510[b]	63[c]	0.08[j]	0.12[k]
Other Facilities				
Capenhurst	-	67	-	0.02
URENCO UK	470[d]	67[e]	0.21[l]	0.02[e]
Springfields	619	68	0.01	0.01
Sellafield	1184	3749	1.19[o]	3.74[o]
Drigg LLWR	61	27	0.02[m]	-
Reference Facilities				
Mine	1993[f]	-	6.18-9.97[n]	-
Preparation Facilities	8942[g]	-	1.16-3.60[o]	-
LLW/ILW	61[h]	-	0-0.12[o]	-
HLW	61[h]	-	0-0.12[o]	-
New Build				
EPR	417[i]	-	0.35[p]	-
AP1000	417[i]	-	0.67[q]	-
Processes				
Transport	-	-	0.1[r]	0.1[r]

Table 52 Employment and doses to the workforce.

a. Except where indicated, data from [139].

b. [33].

c. Assumed to be same as for Wylfa, due to similar outputs.

d. [196].

e. Assumed to be same as for Capenhurst.

f. [30].

g. Taken from Table 46, and averaged over 2005 – 2009 period.

h. Assumed to be same as for Drigg LLWR.

i. [34].

j. [23].

k. [15] – gives collective dose as 12.23 man-Sv for decommissioning a PWR. Here assumed this figure applies to AGRs, and also assumed the dose is distributed evenly over 100 years. This figure is therefore for collective dose.

l. [102].

m. Assumed all dose is to operational workers, as discussed in [15].

n. [24].

o. [140].

p. [10]

q. [204].

r. [15]. Figure is collective dose per GWa, and accounts for all occupational exposure involved in transporting uranium from the mines.

UK Nuclear Plants	Collective Dose (man-Sv)[a]	
	Operation	Decommissioning
Calder Hall	-	0
Dounreay	-	0
Chapelcross	-	0.15
Berkeley	-	0
Bradwell	-	0
Windscale	-	-
Hunterston A	-	0
Hinkley Point A	-	0
Dungeness A	-	0.14
Trawsfynydd	-	0
Sizewell A	-	0.04
Winfrith	-	0
Oldbury	1.32	0.18
Wylfa	0.32	0.04
Hunterston B	0.54	0.07
Hinkley Point B	0.43	0.06
Hartlepool	0.48	0.07
Dungeness B	0.17	0.02
Heysham 1	0.23	0.03
Heysham 2	0.26	0.04
Torness	0.13	0.02
Sizewell B	0.03	0
Other Facilities		
Capenhurst	-	0.00
URENCO UK	-[b]	0.00[b]
Springfields	0.41[c]	0.41[c]
Sellafield	2.33	-
Drigg LLWR	-	-
Reference Facilities		
Mine	1.45[d]	-
Preparation Facilities	0.41[e]	-
LLW/ILW	-[f]	-
HLW	-[f]	-
New Build		
EPR	0.11[g]	-
AP1000	0.25[g]	-
Processes		
Transport	0.05	0.05

Table 53 Public collective doses. Note that, to determine collective doses to the European region, these figures should be multiplied by 8.77. The determine collective doses to the world region, these figures should be multiplied by 80.24. See Table 51.

a. Average annual collective doses to EU population are taken from [92]. The UK dose is then assumed to be 11.4% of this dose, as calculated by comparison of UK and EU doses as given in [9] and [202]. Decommissioning doses for currently operational plants are calculated from observation of the relative drop in dose from the plants that have transferred from the operational to the decommissioning stage.

b. Assumed to be the same as observed at Capenhurst.
c. Taken from [15]. Decommissioning assumed to be the same as for operation.
d. [15] puts collective dose from uranium mine to typical regional population at 29 manSv over 20 year life of the mine. Annual collective dose is therefore 29/20 = 1.45 manSv.
e. Assumed to be same as the enrichment stage.
f. As used in [15].
g. See Table 51.

Release Category	Release Frequency per Reactor Year	Mean Collective Worker Dose, man-Sv	Mean Collective Public Dose, man-Sv
Containment Failure - Early	7.5×10^{-9}	42.3	8,468
Containment Failure - Intermediate	1.9×10^{-10}	25.9	7,004
Containment Failure - Late	3.5×10^{-13}	0.04	73.7
Intact Containment	2.2×10^{-7}	0.02	7.2
Containment Bypass	1.1×10^{-8}	137	32,163
Containment Isolation Failure	1.3×10^{-9}	51.0	20,049
Total	2.4×10^{-7}	256	67,764

Table 54 AP1000 Release frequencies and resulting collective doses. See [203].

Group	Group Size	Dose (Sv)	Loss of Life Expectancy per Person (year)
Public	70,000,000	9.7×10^{-4}	0.002
Plant Operators	20	Killed immediately (assume receive 10 Sv each)	39.5
Plant Operators	100	0.56	0.83
Large Accident Frequency (year^{-1})			2.4×10^{-7}
Expected Loss of Life Expectancy			5.7×10^{-10}
Expected Collected Loss of Life Expectancy			0.040

Table 55 Data for reference large nuclear accident.

Materials		Mt required /GWa
Uranium Mine[a]	Steel	4.2×10^{-4}
	Concrete	1.7×10^{-4}
Nuclear Power Plants[b]	Steel	5.7×10^{-4}
	Concrete	8.1×10^{-3}
Waste Storage & Disposal[c]	LLW/ILW - Aggregates	4.6×10^{-4}

Table 56 Material requirements for new build.

a. Steel and concrete requirement of 0.5 Mt and 0.2 Mt is for coal mine [15] is assumed applicable to uranium mine. Normalised against lifetime output of mine of 1,186 GWa, taken from data for Rossing mine [208]. Other mines have larger lifetime outputs (e.g. from previous reference, Olympic Dam mine has an expected lifetime output of 16,000 GWa) which would produce a lower material requirement per GWa. However, used higher risk factor here in interest of conservatism.

b. [7] gives materials requirement of the EPR. Normalised against the lifetime output of the EPR, which is 89 GWa. The materials requiring the next greatest quantity are copper and aluminium, requiring 3.7×10^{-6} and 1.6×10^{-6} Mt/GWa respectively.

c. Material requirements are taken from [140]. Only aggregates are used in massive quantities, although other materials are also used.

Current HEP (£M/GWa)	Immediate Impacts		Delayed Impacts		Abnormal Impacts
	Occupational	Public	Occupational	Public[a]	
Extraction	0 – 0.024	-	0.013 – 0.023	0.005	-
Preparation	0.006 – 0.097	-	0.001 – 0.002	0.005 – 0.006	-
Generation	0.003 – 0.725	-	0.070 – 0.079	0.086 – 0.096	0.007[b,c]
Reprocessing	0.011 – 0.382	-	0.159 – 0.178	0.026 – 0.029	-
Waste Storage and Disposal	negligible	-	0 – 0.001[d]	negligible	-
Materials	0.012 – 0.029	-	0 – 0.009	0.099 – 0.577[e]	-
Transport	0 – 0.009	0 – 0.009	0	0.011 – 0.061[f]	-
Total	0.032 – 1.27	0 – 0.009	0.244 – 0.292	0.231 – 0.773	0.007

Table 57 Current hazard elimination premiums for various impacts arising at different fuel chain stages.

a. For UK region only. To determine European region impact, multiply by 8.77. To determine world impacts, multiply by 80.24.
b. Mostly delayed public risk, less than 1% immediate occupational risk.
c. About 30% is a financial HEP, resulting from environmental impacts.
d. Impacts are mostly due to dust exposure, with less than 1% due to radiation.
e. Impacts are due to pollution.
f. Impacts are mostly due to pollution, with less than 1% due to radiation.

Incremental HEP (£M/GWa)	Immediate Impacts		Delayed Impacts		Abnormal Impacts
	Occupational	Public	Occupational	Public[a]	
Extraction	0.001 – 0.033	-	12,700 – 22,900	4,500 – 5,000	-
Preparation	0.006 – 0.097	-	0 – 0.001	negligible	-
Generation	0.002 – 0.409	-	0.029 – 0.032	0.015 – 0.017	0.007[b,c]
Reprocessing	-	-	0.009 – 0.010	0.026 – 0.029	-
Waste Storage and Disposal	0 – 0.001	-	0 – 0.001	negligible	-
Materials	0.002 – 0.009	-	0 – 0.001[d]	0.006 – 0.037[e]	negligible[f,g]
Transport	0.001 – 0.013	0.001 – 0.013	negligible	0.011 – 0.061[h]	-
Total	0.011 – 0.561	0.001 – 0.013	0.051 – 0.067	0.063 – 0.148	0.007 – 0.008

Table 58 Incremental hazard elimination premiums for various impacts arising at different fuel chain stages.

a. For UK region only. To determine European region impact, multiply by 8.77. To determine world impacts, multiply by 80.24.
b. Mostly delayed public risk, less than 1% immediate occupational risk.
c. About 30% is a financial HEP, resulting from environmental impacts.
d. Impacts are mostly due to dust exposure, with less than 1% due to radiation.
e. Impacts are due to pollution.
f. All resulting in immediate occupational impacts.
g. 5% is a financial HEP resulting from the environmental cost of coal accidents.
h. Impacts are mostly due to pollution, with less than 1% due to radiation.

Chapter 16 Fossil Fuel Chains

16.1 Description of the Fuel Chains

The two electricity generating technologies that use fossil fuel that will be analysed here are coal and natural gas. Fossil fuel chains are similar to nuclear chains in that there are a number of stages from extraction to disposal which present risks to workers and to the public. Unlike nuclear, however, fossil fuels can be extracted within the UK. There are still many operational coal mines, both underground and opencast, and the UK continental shelf is home to many offshore rigs that extract oil and gas. Some of the main risks at the extraction stage are from major accidents, both in coal mines and as a result of offshore drilling activities. Coal worker's pneumoconiosis (CWP) is also an important source of risk, although the impacts have much uncertainty. Immediate fatalities to coal miners during normal operation are also a major source of risk.

The preparation stage, which includes treatment of natural gas at terminals and storage of fossil fuels before they are used, has been assessed for the operational sub-stage. Construction and decommissioning risks of new and existing preparation facilities has been neglected, but are expected to be small on a per GWa basis.

Construction, operation and decommissioning of power plants have been included. The gas plants are assumed to be combined-cycle gas turbines (CCGT), while the coal plants are assumed to be typical of current build. The plant parameters for the new build will be described in the following section.

The reprocessing stage is not relevant to either of the fuel chains and consequently has not been included here. The waste disposal phase is not relevant to the gas chain, but is for coal, where the disposal of coal ash presents radiological risks to workers and to the public.

16.2 Plant Parameters

Table 60 lists all combined-cycle gas turbines currently in operation in the UK. Data was only available for the operational start date and capacity for each plant. The data for the lifetimes of operation and construction were obtained from Mott Macdonald (2010) [136], which estimates that the time for construction of a gas plant is three years, and operation time is 30 years. It is also assumed that decommissioning time is equal to construction time. The capacity factor is assumed to be the same for each currently operational plant. Data from DECC (2011d) [51] indicate that, over the period 2006 – 2010, the capacity factor for all gas turbines is 63%. Capacity and capacity factors for new build were taken from [136], which assume new CCGTs have a capacity of 0.83 GW, and operate at 90% capacity.

Table 59 shows currently operational coal plants within the UK. Again, data was only available for the operational start date and capacity for each plant. Lifetimes obtained from [136] give construction (and hence decommissioning) times as four years, and operational times as 50 years, although there are some exceptions, as explained in the notes. Data for new build are also taken from this source, as for new gas plants. New coal plants are assumed to have a capacity of 1.6 GW, and a capacity factor of 90%.

Extraction facilities are assumed to be constructed, operated and decommissioned continuously throughout this period, and the parameters for new CCGT and coal plants are shown in Table 61.

16.3 Extraction

Data for immediate fatalities at the extraction stage are provided in Table 86 in Appendix D. There have been forty fatalities involved with offshore oil and gas rigs over the past five years. Nine of these have been small single fatality accidents, and 31 have been as a result of a large multiple fatality accident, as is shown in Table 27. Section 14.7 discussed how these fatalities were apportioned. The nine single fatalities were used to estimate the immediate occupational fatality risk from normal operation, while the multiple fatalities were considered for use in the abnormal operation category, but ultimately rejected in favour of more conservative estimates.

No attempt has been made to apportion the fatalities to gas or oil fuel chains, even though some of the fatalities occurred on gas rigs and some on oil rigs. This is because whether the extraction platform is producing oil or gas (or both) is not the relevant factor in the fatalities, indeed, some rigs produce both oil and gas. The fatalities are therefore normalised against the total electrical energy output equivalent of all gas and oil production, listed in Table 88 and Table 89, in order to derive the exposure rate. Over the period 2006 – 2010, there has been some 624 GWa of electrical energy equivalent extracted from the UK continental shelf, with 72% of that coming from natural gas. Furthermore, the exposure rate has been split equally amongst the construction, operation and decommissioning stages of the extraction phase, as again, the process that occurs aboard the platform is not a pertinent factor for the observed fatalities.

For extraction of coal, Table 86 shows that there have been eleven fatalities in coal mines over the past five years. The HSE description of these fatalities (HSE (2011b) [105]) indicates that eight of the fatalities occurred in operational activities, whilst the remaining three occurred in construction activities. These are then normalised against the electrical energy output equivalent of the coal mined during this period, as given by Table 90. In addition to the immediate accidental fatalities, coal miners also suffer from risks of coal worker's pneumoconiosis (CWP), which is a type of lung disease, colloquially known as "black lung", resulting from inhalation of coal dust. This impact has been discussed in section 14.3 when estimating the effects of steel. The method for estimating the effect of exposures to coal dust is based on extrapolation of current mortality rates forward to a point in time when the average age of those who are currently working is equal to the average age of death for CWP sufferers. This is based on the method used by Ferguson (1989) [83], and is discussed in more detail in Appendix C. It was found that the loss of life expectancy was 0.01 – 5.4 years/Mt. There is considerable uncertainty over these figures due to the extrapolation method used. This figure is then normalised against the amount of coal required to generate one GWa of electricity. This can be calculated from DECC statistics DECC (2011a) [48], as about 3.3 Mt/GWa. The pneumoconiosis impacts are therefore 0.02 – 17.5 years/GWa. However, this figure may be affected by trends in mining methods. If opencast mining becomes more prevalent in comparison to deep underground mining, then the incidence of CWP will be reduced, and the above figure will be an overestimate.

Workers in both the coal and the gas industry are also exposed to radiation. At the extraction stage, workers on a gas platform receive doses from rocks under the sea which contain high concentrations of uranium. In coal mines, as in uranium mines, workers are exposed to radon and its associated decay products. These effects were discussed in sections 14.3 and 14.7. The HSE's Central Index of Dose Information (HSE, (2004) [99]) was used to estimate the occupational exposures to coal miners and offshore workers, which is shown in Table 62. The impacts are presented in Table 34 in terms of the years of life lost per Mt. To convert these figures into years of life lost per GWa, it is necessary to multiply by 3.3 Mt/GWa for coal, and 1.6 Mt/GWa for gas and oil.

The delayed public fatality impacts are negligible as both radioactive and particulate matter emissions from extraction facilities are low.

The extraction of coal and gas also carries major accident risks in which large numbers of fatalities can occur. These can be caused by mine collapse, pipeline explosions, and crashes during transportation to and from the offshore rig. Such accidents result in fatalities mostly to the workforce. These fatalities were discussed in the materials chain section, for steel in section 14.3, and plastic in section 14.7. The impacts in terms of lost life expectancy per Mt are shown in Table 34. These can be converted into an impact per GWa by multiplying by the same factors as given above. This also applies to the financial impacts associated with major accidents.

16.4 Preparation

Fatalities during the operation of gas and coal preparation facilities in the UK over the period 2006 – 2010 are listed in Table 86. These are then normalised against the respective electrical output of each technology to arrive at an exposure rate. The risks of constructing and decommissioning such facilities are assumed to be negligible on a per GWa basis, and are not assessed here. Immediate occupational fatalities are assumed to be the only significant risk at this stage, and public and occupational delayed fatalities are assumed negligible

16.5 Generation

Fatalities involved with the construction of gas plants are accounted for in Table 86. The fatalities are normalised against the amount of assumed electricity generated over the lifetime of the facilities which were constructed during this period. There have been no fatalities involved with the construction of coal plants, as there have not been any constructed during the five year period under review. For this reason, it has been assumed that the exposure rate from the construction of coal plants is equal to the exposure rate from construction of gas plants. These are also broadly similar to the exposure rate from constructing a nuclear plant.

Operational exposure rates are again derived from Table 86, with the appropriate normalisation. There have been three fatalities in coal power stations and two in the operation of gas stations over the period 2006 – 2010. Decommissioning rates were assumed to be equal to construction rates, as the two processes are similar.

There are some occupational radiological risks at the power plant stage, as workers can also be exposed to natural radioactivity contained in the natural gas and the coal ash. The assumed collective doses are presented in Table 62. The use of coal and gas in power stations also exposes the general public to radiation causing delayed fatality risks. The collective dose resulting from a coal station is comparable to that from a nuclear station, although coal stations typically produce more electricity. The collective doses are shown in Table 63.

One important source of risk from fossil fuel generation is from the emission of particulate matter. The combustion of coal and gas results in large amounts of quantities of PM2.5 being emitted into the atmosphere. These then become circulated over Europe, which results in many individuals being exposed to increased concentrations of particulate matter, causing premature mortality. The impacts of these emissions are estimated from the PM10 emission rates of the currently operational coal and gas stations owned by E.On UK plc (2007a) [75]. The total emissions for all owned coal plants, and all owned gas plants can then be normalised against the electrical energy output by these plants, to give a figure for PM10 emissions per GWa. This can then be multiplied by 56% (the proportion of PM2.5 in PM10 from emissions from the energy industry see DEFRA (2009b) [59]) to get the PM2.5 emissions per GWa. This can then be used to calculate the collective exposure to increased concentrations of PM2.5, and hence calculate the loss of life expectancy and HEP. The raw data is shown in Table 64 and Table 65. This can then be used to estimate the collective exposure from all currently operational coal and gas plants in the UK. Emissions from new build plants are estimated from the environmental statements for the new replacement units at the Kingsnorth power station for coal (see E.On UK plc (2007b) [76]) and the Willington C and Blythe Park CCGT power stations for gas, see RWE npower (2009) [173], and Parsons Brinkerhoff (2009) [156]. The gas references indicate that particulate matter emissions will be negligible for new build plants, and so no impact is taken for new gas plants. The impact from coal is shown in Table 64.

Other impacts, such as those resulting from emissions of toxic substances from coal combustion have not been quantified, due to lack of available data. Arsenic, cadmium, chromium and nickel are all known human carcinogens emitted from coal stations, but their impact on human mortality has not been adequately studied, and so no attempt at quantification has been made here. However, these toxins can become widely circulated, and so the true impact may be substantial.

16.6 Waste Disposal

Reprocessing is not an applicable stage to either gas or coal energy technologies. Waste disposal is applicable to coal as the ash by-product of combustion is disposed of at special facilities. The main risk in this area arises from radiation doses from the coal ash. The collective doses to workers and to the public are shown in Table 62 and Table 63. The doses are very small and the resulting impact is negligible when compared to other sources of risk.

16.7 Materials

The stages of the fossil fuel chain that are assumed to undergo construction activities and hence require materials are the extraction stage and the generation. The materials requirements are therefore for coal mines, offshore rigs and gas pipelines, and the coal and CCGT power plants. It is assumed that the preparation stage and waste disposal stage of the coal fuel chain will not need any new facilities constructed as many such facilities are already in place. The material requirements per GWa for the relevant facilities are shown in Table 66 and Table 67.The risk factors shown in Table 36 and Table 37 can then be applied to determine the impacts associated with these materials per GWa. As was explained in section 15.8, only the material risks classed as "post-decommissioning" in Table 36 and Table 37 contribute to current impacts. The risks classed as "pre-construction" contribute to the incremental impacts.

16.8 Transportation

The transport risks considered are for movement of the construction materials and the raw materials required for manufacturing these materials. The assumptions are the same as described in section 14.2. Transportation of the coal from the mine to the power plant is also included, and it assumed that it is carried 50km entirely on the railways. Half of the transportation fatalities have been ascribed to occupational impacts, and half are ascribed to immediate public impacts.

As with the nuclear transportation impacts discussed in section 15.9, all transportation from the power plant to the waste disposal/recycling facility contributes to the current risks, while all transport up to the power plant contribute to the incremental risks.

16.9 Summary and Discussion

The HEP's for the current and incremental risks for all stages of the coal fuel chain are shown in Table 68 and Table 69. The associated HEP's for the natural gas fuel chain are shown in Table 70 and Table 71.

The results show that, for coal, by far the greatest risks are public delayed fatalities arising from pollution emissions from generating stations. This is true for both current and incremental risks. The risks of coal mining are also relatively high. This is due to two factors: (i) fatalities from mining accidents and (ii) exposures to dust, which causes pneumoconiosis. It may be noted that tighter safety measures in many parts of the world have been reducing steadily the future health effects from this latter hazard.

Pollution emissions from transportation and materials processes also present comparatively high risks. As is the case with radiation impacts, the risks from low doses are subject to large uncertainty. As was discussed above, the impacts of carcinogenic substances emitted from coal burning have not been quantified due to lack of available data relating the exposures of these substances to human mortality. These impacts may, however, be substantial, and this should be borne in mind when viewing the results.

For the gas results, the tables show that the greatest risk posed here is from the pollution emissions at the generation stage for current risks only. This is not a major impact for the incremental risks as the new gas plants are assumed to emit negligible amounts of particulate matter. Another important impact is the pollution emissions from the construction materials chain. Other significant risks are due to abnormal operation at the extraction stage, from which there have been a number of offshore accidents and gas explosions. It should be noted that, although current technologies are assumed to be used over the 60 year period of analysis (as was discussed in chapter 12), gas production will arguably be the first to utilise new technologies such as shale gas, and gas to liquids. The risks from these technologies are highly uncertain, but will be of a different nature to those from conventional pipeline gas presented in this study.

For both gas and coal, the greatest risks arise from the delayed public impacts, followed by the immediate occupational impacts and the abnormal operation impacts. Immediate public impacts and delayed occupational impacts are comparatively low. Also, for both technologies, the public delayed fatalities have smaller incremental risks than current risks, indicating that additional facilities pose less risk than is currently being experienced. However, the other impact categories have greater incremental risks than current risks, meaning that expansion of these technologies poses greater risks than is currently being experienced, although many of these additional risks arise indirectly in the construction materials chain.

UK Coal Stations	Operation Started[a]	Operation Lifetimes (year)[b]	Net Capacity (GW)[a]	Capacity Factor[e]	Output Remaining from 2010 (GWe)
Kilroot	1981	50	0.662	0.62	8.56
Drax	1974	50	3.87	0.62	33.37
Ironbridge	1970	46[c]	0.97	0.62	3.58
Ratcliffe	1968	50	2.00	0.62	9.85
Cottam	1969	50	2.008	0.62	11.13
West Burton	1967	50	2.012	0.62	8.67
Eggborough	1967	50	1.96	0.62	8.45
Rugeley	1972	50	1.006	0.62	7.44
Aberthaw B	1971	50	1.586	0.62	10.75
Cockenzie	1967	49[c]	1.152	0.62	4.26
Longannet	1970	50	2.304	0.62	14.19
Tilbury B	1968	48[c]	1.063	0.62	3.93
Uskmouth	2000	25[d]	0.363	0.62	3.35
Ferrybridge C	1966	50[c]	1.96	0.62	7.24
Fiddler's Ferry	1971	50	1.98	0.62	13.41
Didcot A	1972	44[c]	1.958	0.62	7.24
Kingsnorth	1970	46[c]	1.94	0.62	7.17
Reference Facilities					
Coal Mine	2010	60	N/A	N/A	N/A
Preparation Facilities	2010	60	N/A	N/A	N/A
Ash Disposal	2010	60	N/A	N/A	N/A

Table 59 Operation and decommissioning lifetimes of UK coal facilities, including assumed lifetimes for reference facilities, and capacities, capacity factors and remaining output from 2010 to 2070.

a. [51]

b. [136], except where indicated.

c. [2]

d. [172]

e. See Table 87. Averaged over 2006 – 2010.

UK Gas CCGT Station	Operation Started[a]	Net Capacity (GW)[a]	Capacity Factor[b]	Output Remaining from 2010 (GWe)
Baglan Bay	2002	0.58	0.63	8.010
Barking	1994	1.00	0.63	8.864
Barry	1998	0.23	0.63	2.621
Glanford Brigg	1993	0.26	0.63	2.140
Killingholme 2	1994	0.67	0.63	5.895
Kings Lynn	1996	0.34	0.63	3.444
Langage	2010	0.91	0.63	17.191
Peterborough	1993	0.41	0.63	3.334
Roosecote	1991	0.23	0.63	1.595
Corby	1993	0.40	0.63	3.301
Coryton	2001	0.80	0.63	10.637
Deeside	1994	0.50	0.63	4.432
Cottam Development Centre	1999	0.40	0.63	4.812
Connahs Quay	1996	1.38	0.63	13.980
Enfield	1999	0.39	0.63	4.716
Killingholme	1993	0.90	0.63	7.408
Sutton Bridge	1999	0.80	0.63	9.624
South Humber Bank	1996	1.29	0.63	13.018
Immingham	2004	1.24	0.63	18.843
Keadby	1994	0.75	0.63	6.639
Marchwood	2009	0.84	0.63	15.461
Medway	1995	0.69	0.63	6.534
Rocksavage	1998	0.81	0.63	9.232
Didcot B	1998	1.43	0.63	16.298
Great Yarmouth	2001	0.42	0.63	5.585
Little Barford	1995	0.67	0.63	6.316
Saltend	2000	1.20	0.63	15.196
Damhead Creek	2000	0.80	0.63	10.131
Shoreham	2000	0.40	0.63	5.065
Rye House	1993	0.72	0.63	5.885
Seabank 1	1998	0.81	0.63	9.254
Seabank 2	2000	0.41	0.63	5.192
Wilton GT2	2005	0.04	0.63	0.665
Spalding	2004	0.88	0.63	13.373
Peterhead	2000	1.18	0.63	14.943
Teesside Power Station	1992	1.88	0.63	14.246
Coolkeeragh	2005	0.41	0.63	6.458
Sandbach	1999	0.06	0.63	0.674

Castleford	2002	0.06	0.63	0.780
Thornhill	1998	0.05	0.63	0.570
Ballylumford C	2003	0.62	0.63	8.971
Reference Facilities				
Gas Platform	2010	N/A	N/A	N/A
Gas Storage/ Terminals etc	2010	N/A	N/A	N/A

Table 60 Operation and decommissioning lifetimes of UK gas CCGT facilities, including assumed lifetimes for reference facilities, and capacities, capacity factors and remaining output from 2010 to 2070.

a. [51]

b. See Table 87. Averaged over 2006 – 2010.

	Lifetimes (year)			Net Capacity (GW)	Capacity Factor
New Build[a]	Construction	Operation	Decomm-issioning		
CCGT	3	30	3	0.83	0.9
Coal	4	40	4	1.6	0.9

Table 61 Assumed construction, operation and decommissioning lifetimes of new CCGT and coal plants, and assumed capacity and capacity factors.

a. [136]

Worker Collective Dose (man-Sv)	Gas	Coal
Extraction	0.11[a]	0.30[c]
Power Plant	1×10^{-4} [b]	6×10^{-4} [d]
Ash Disposal	-	5×10^{-6} [e]

Table 62 Occupational collective doses.

a. [99], proportioned according to percentage of gas extracted from offshore activities.
b. [200] gives range of individual dose from 1E-7 to 1E-4. Here taken 1×10^{-6} as being most appropriate. This is then multiplied by average staff number, taken to be 100, see [141].
c. [99], all mining activities included.
d. [177] gives average dose. Collective dose determined by assuming number of operational coal staff is equal to average number of operational nuclear staff, from Table 52.
e. [177].

Public Collective Dose (man-Sv)	Gas	Coal
Extraction	-	-
Power Plant	0.003[a]	0.14[b]
Ash Disposal	-	0.001[b]

Table 63 Public collective doses.

a. [200]. Average dose is multiplied by 1 million, the assumed upper limit of population residing near to the gas plant.
b. [177]

Particulate Matter Emissions – Coal Plants	PM10 Emissions (kt/a)	Energy Generated (GWa)	PM2.5 Emission Rate (μg.s^{-1}/ GWa)
Ratcliffe	0.146	1.00	2.6×10^{6}
Kingsnorth (original)	0.372	1.12	5.9×10^{6}
Ironbridge	0.328	0.40	1.5×10^{7}
Total	0.846	2.53	6.0×10^{6}
Kingsnorth (new build)	0.20	1.6	2.2×10^{6}

Table 64 Particulate matter emissions from E.On UK coal plants. New Build plant is assumed to operate at full load.

Particulate Matter Emissions – Gas Plants	PM10 Emissions (kt/a)	Energy Generated (GWa)	PM2.5 Emission Rate (μg.s^{-1}/ GWa)
Killingholme	0.011	0.183	1.1×10^{6}
Enfield	0.008	0.247	5.8×10^{5}
CDC	0.009	0.181	8.8×10^{5}
Corby	0.005	0.084	1.1×10^{6}
Connah’s Quay	0.044	0.900	8.7×10^{5}
Total	0.077	1.595	8.5×10^{5}

Table 65 Particulate matter emissions from E.On UK gas plants.

Materials - Coal		Mt Required per Gwa[a]
Extraction - Coal Mine	Steel	0.018
	Concrete	70×10^{-4}
Coal Plant	Steel	8.5×10^{-4}
	Concrete	0.02

Table 66 Material requirements for new coal build, and the safety data for material fabrication.

a. [15]

Materials - Gas		Mt Required per Gwa[a]
Extraction - Gas Platform	Steel	15.0×10^{-4}
	Concrete	2.0×10^{-4}
Extraction - Gas Pipelines	Steel	4.0×10^{-4}
	Concrete	6.0×10^{-4}
Gas Plant	Steel	2.5×10^{-4}
	Concrete	60×10^{-4}

Table 67 Material requirements for new gas build, and the safety data for material fabrication.

a. [15]

Current HEP (£M/GWa) - Coal	**Immediate Impacts**		**Delayed Impacts**		**Abnormal Impacts**
	Occupational	**Public**	**Occupational[a]**	**Public[b]**	
Extraction	0.379 – 1.933	-	0.009 – 2.40[c]	-	0.658 – 0.808[d,e]
Preparation	0.001 – 0.286	-	-	-	-
Generation	0.015 – 0.666	-	negligible	69.0 – 401[c]	-
Reprocessing	-	-	-	-	-
Waste Storage and Disposal	-	-	negligible	negligible	-
Materials	0.200 – 0.855	-	-	0.332 – 1.93	-
Transport	0.002 – 0.086	0.002 – 0.086	-	0.504 – 2.93	-
Total	0.596 – 3.83	0.002 – 0.086	0.009 – 2.40	69.8 – 406	0.658 – 0.808

Table 68 Current coal hazard elimination premiums for various impacts arising at different fuel chain stages.

a. Delayed occupational impacts are due to dust, except where otherwise indicated.
b. Delayed public impacts are due to pollution, arising from exposures to particulate matter, except where otherwise indicated.
c. Less than 1% due to radiation.
d. All resulting in immediate occupational impacts.
e. 5% is a financial HEP resulting from the environmental cost of coal accidents.

Incremental HEP (£M/GWa) – Coal	Immediate Impacts		Delayed Impacts		Abnormal Impacts
	Occupational	Public	Occupational[a]	Public[b]	
Extraction	0.423 – 2.63	-	0.002 – 2.39[c]	-	0.666 – 0.815[d,e]
Preparation	0.001 – 0.286	-	-	-	-
Generation	0.009 – 0.387	-	negligible	52.0 – 302[c]	-
Reprocessing	-	-	-	-	-
Waste Storage and Disposal	-	-	negligible	negligible	-
Materials	0.001 – 0.630	-	0 – 0.014	0.361 – 2.10	0.004 – 0.005[d, e]
Transport	0.004 – 0.153	0.004 – 0.156	-	0.390 – 2.27	-
Total	0.582 – 4.09	0.004 – 0.156	0.002 – 2.40	52.8 – 307	0.670 – 0.821

Table 69 Incremental coal hazard elimination premiums for various impacts arising at different fuel chain stages.

a. Delayed occupational impacts are due to dust, except where otherwise indicated.

b. Delayed public impacts are due to pollution, arising from exposures to particulate matter, except where otherwise indicated.

c. Less than 1% due to radiation.

d. All resulting in immediate occupational impacts.

e. 5% is a financial HEP resulting from the environmental cost of coal accidents.

Current HEP (£M/GWa) - Gas	Immediate Impacts		Delayed Impacts		Abnormal Impacts
	Occupational	Public	Occupational[a]	Public[b]	
Extraction	0.003 – 0.047	-	negligible	-	0.115 – 0.142[d,e]
Preparation	0.002 – 0.054	-	-	-	-
Generation	0.009 – 0.273	-	negligible	9.04 – 52.6[c]	-
Reprocessing	-	-	-	-	-
Waste Storage and Disposal	-	-	-	-	-
Materials	0.024 – 0.100	-	-	0.084 – 0.486	-
Transport	0 – 0.009	0 – 0.009	-	-	-
Total	0.038 – 0.483	0 – 0.009	negligible	9.12 – 53.1	0.115 – 0.142

Table 70 Current gas hazard elimination premiums for various impacts arising at different fuel chain stages.

a. Delayed occupational impacts are due to dust, except where otherwise indicated.
b. Delayed public impacts are due to pollution, arising from exposures to particulate matter, except where otherwise indicated.
c. Less than 1% due to radiation.
d. All resulting in immediate occupational impacts.
e. 22% is a financial HEP resulting from the environmental cost of gas accidents.
f. 5% is a financial HEP resulting from the environmental cost of coal accidents.

Incremental HEP (£M/GWa) - Gas	Immediate Impacts		Delayed Impacts		Abnormal Impacts
	Occupational	Public	Occupational[a]	Public[b]	
Extraction	0.009 – 0.141	-	negligible[c]		0.115 – 0.142[d,e]
Preparation	0.002 – 0.054	-	-	-	-
Generation	0.008 – 0.243	-	negligible	negligible[c]	-
Reprocessing	-	-	-	-	-
Waste Storage and Disposal	-	-	-	-	-
Materials	0.024 – 0.100	-	0.006 – 0.007[c]	0.836 – 1.33	0.001[d,f]
Transport	0.007 – 0.023	0.001 – 0.024	-	0.011 – 0.063	-
Total	0.049 – 0.560	0.001 – 0.024	0.006 – 0.007	0.848 – 1.39	0.116 – 0.143

Table 71 Incremental gas hazard elimination premiums for various impacts arising at different fuel chain stages.

a. Delayed occupational impacts are due to dust, except where otherwise indicated.
b. Delayed public impacts are due to pollution, arising from exposures to particulate matter, except where otherwise indicated.
c. Less than 1% due to radiation.
d. All resulting in immediate occupational impacts.
e. 22% is a financial HEP resulting from the environmental cost of gas accidents.
f. 5% is a financial HEP resulting from the environmental cost of coal accidents.

Chapter 17 Wind Fuel Chains

17.1 Description of the Fuel Chains

Onshore wind and offshore wind are the two electricity generating technologies that are currently undergoing the most rapid expansion in the UK. These technologies offer the greatest prospects of producing substantial quantities of electricity derived from renewable fuels. The fuel chains are much simpler than for the fossil or nuclear chains. There is no extraction, preparation, reprocessing or waste disposal needed in the generation of electricity from wind. The remaining sources of risk occur in the construction, operation and decommissioning of the wind turbines (which will be categorised as power plants here), and in the impacts from the material requirements, which also entails transport risks.

The sources of risk at the generation stage involve immediate occupational fatalities at the construction stage for both onshore and offshore technologies. There are also risks at the operational stage for onshore wind for both workers and the public, although there is much uncertainty inherent in some of the figures. The decommissioning risks are assumed to be equal to the construction risks. There are no impacts from exposures to radiation, particulate matter, or mineral dust.

The materials requirement for both technologies was found to be quite large when compared with the fossil and nuclear technologies. Materials other than steel and coal are required in massive quantities, and these result in some substantial human health impacts. The large material requirements also results in comparatively large transportation impacts.

17.2 Plant Parameters

Table 72 presents the data used for currently operational onshore and offshore wind turbines. Assumed lifetimes of operation and construction were obtained from Mott Macdonald (2010) [136]. These are two years for construction and 24 years for operation, for both on and offshore turbines. As with the fossil chains, it is also assumed that decommissioning time is equal to construction time. The capacity factors for all onshore and offshore wind turbines were obtained from DECC (2011f) [53], which show that over the period 2006 – 2010, onshore wind has produced on average at 26% of maximum capacity, while offshore wind has averaged 29% of maximum capacity. The data for electricity production and capacity installed is shown in Table 87 in Appendix E. Capacity factors for new build are taken from [136], which use 28% for new onshore turbines, and 41% for new offshore turbines.

17.3 Generation

Fatalities involved with the construction and operation of wind turbines are shown in Table 86 in Appendix D. There have been three fatalities attributable to onshore wind, one of which was during construction and two of which were during operation. There have also been two fatalities attributable to offshore wind, both occurring during construction. Uncertainty is accounted for by using Poisson statistics for each of these stages. Events with low counts necessarily have wide confidence limits, and so there is much uncertainty about the true size of the risk from the wind technologies. It is not possible to assess the impacts with any more accuracy until the technologies have become more widespread. Although no fatalities have occurred during the operation of offshore wind, impacts have still been ascribed to this area using confidence limits derived from Poisson statistics with a zero count. Transporting workers to and from offshore facilities has been a quite dangerous activity historically, with 31 such deaths occurring over the most recent five years, as shown in Table 86 in Appendix D. There have also been a number of near misses at various UK offshore wind farms, for example, see DECC (2011j) [57], and so it is judged that treating the operational fatalities in this way is valid. Construction fatalities are normalised against the amount electricity generated over the lifetime of plants constructed the period 2006 - 2010, in order to derive the associated exposure rate. This figure includes new turbines being constructed but not yet operational, which is important to include as wind technology is currently expanding rapidly. Operational fatalities are normalised against the amount of electricity generated by onshore and offshore wind turbines over the same five year period. There has not been any major decommissioning of wind turbines as yet, and so it is not possible to estimate this risk from any observed data. Instead, it is assumed that the exposure rate associated with decommissioning is the same as for construction activities.

One important impact that has been included for onshore wind is the risk of immediate fatalities to members of the public. Quantifying the risk from this source is difficult as there have not been any public fatalities in the UK between 2006 and 2010. However, experience from other countries, such as the USA and Canada, indicates that this risk is not negligible, see Gipe (2009) [87]. In these situations risks can arise, for example, from the collapse of turbines and from collisions with light aircraft. An initial estimate of the public risk can be made using Poisson statistics. For a count of zero, the 95% confidence limits are 0 – 3.7 fatalities over the period, with central estimate of 1.8 fatalities. This compares well with the two public fatalities observed during this period in Canada, where both electrical output and the rate of construction of onshore wind power is similar to the UK. The UK prediction is thus judged to be valid, but the scarcity of data means that there is much uncertainty associated with this figure. The exposure rate for public fatalities can then be calculated by normalising against the amount of electricity generated over the period.

17.4 Materials

Material requirements are an important source of risk for the wind technologies. Wind turbines require much more material than nuclear or fossil fuels to generate the same amount of electricity. The material requirements for onshore and offshore turbines are presented in Table 74, for materials used in massive quantities. As discussed in chapter 14, materials required in quantities greater than 10^{-4} Mt/GWa are classed as a “massive” requirement, and are included in the analysis. Onshore wind requires 8.5×10^{-2} Mt of materials per GWa, whilst offshore wind requires 2.8×10^{-2} Mt per GWa. As well as needing steel and concrete, wind farms also require other materials such as plastic, glass, copper and other non-ferrous metals in massive quantities. The impacts of these materials can then be calculated from the risk factors shown from Table 36 to Table 42. Only the material risks classed as “post-decommissioning” in these tables contribute to current impacts. The risks classed as “pre-construction” contribute to the incremental impacts.

It is also worth noting that much attention has been given recently to the environmental and health effects of the Chinese rare earth industry, which mines neodymium used in permanent magnets in large wind turbines. Including such effects could be expected to increase somewhat the risk from wind power. However, this analysis only includes materials that are used in large quantities and neodymium does not fall in this category. These effects have therefore not been included.

17.5 Transportation

Transport risks use the assumptions as described in section 14.2. The risk factors for each material are provided in the tables to chapter 14, from Table 36 to Table 42. Although there is some transportation risk involved in the transportation of components offshore, these are taken to be negligible on a per GWa basis. Transportation of the materials after the turbine has been decommissioned is also included. Half the transportation fatalities are apportioned to occupational impacts, and half to public impacts. The assumptions from previous sections are retained here, namely that all transportation from the power plant to the waste disposal/recycling facility contributes to the current risks, while all transport up to the power plant contribute to the incremental risks.

17.6 Summary and Discussion

The current and incremental impacts for the onshore wind fuel chain are summarised in terms of the HEP’s in Table 75 and Table 76. The equivalent HEP’s for the offshore wind fuel chain are shown in Table 77 and Table 78.

Onshore wind poses comparatively large impacts at all relevant stages. The largest impacts are due to immediate occupational fatalities at the generation stage. This is followed by immediate public fatalities also at the generation state, and delayed public fatalities due to pollution from the construction materials chain. Immediate and delayed public impacts are similar in magnitude when summed over the whole fuel chain. These results are true for both current impacts and incremental impacts. However, there is considerable uncertainty associated with these figures and the upper end of the figures may be an overestimate. Incremental impacts are greater than current impacts, meaning that expansion of onshore wind electricity generation will pose greater risks than are already being experienced. Total public impacts are similar to total occupational impacts, and total immediate impacts are considerably larger than total delayed impacts. The risks from abnormal operation are comparatively small.

For offshore wind, the impacts are similar to those of onshore wind, except that the immediate public risks are smaller. The greatest impact again arises from immediate occupational impacts to workers at the generation stage. There are also large immediate impacts to workers in the construction materials chain. Delayed public risk from pollution is also an important source of risk in this chain. As with onshore wind, incremental impacts from offshore wind are greater than current impacts.

Wind - Current Plants	Lifetimes (year)[a]			Capacity Factor[b]
	Construction	Operation	Decomm-issioning	
Onshore Wind	2	24	2	0.26
Offshore Wind	2	24	2	0.29

Table 72 Construction, operation and decommissioning lifetimes, and capacity factors for current wind plants.

a. [136]

b. See Table 87. Average over 2006 – 2010.

Wind – New Build Plants	Lifetimes (year)[a]			Capacity Factor[a]
	Construction	Operation	Decomm-issioning	
Onshore Wind	2	24	2	0.28
Offshore Wind	2	24	2	0.41

Table 73 Construction, operation and decommissioning lifetimes, and assumed capacity factors for new build wind plants

a. [136]

Materials (Mt/GWa)	Onshore Wind[a]	Offshore Wind[a]
Iron & Steel	2.0×10^{-2}	2.2×10^{-2}
Concrete	6.3×10^{-2}	9.3×10^{-4}
Copper	2.4×10^{-4}	7.4×10^{-4}
Lead	-	1.6×10^{-3}
Zinc	-	5.4×10^{-4}
Aluminium	1.4×10^{-4}	4.4×10^{-4}
Glass	1.7×10^{-3}	1.2×10^{-3}
Plastic	3.5×10^{-4}	7.7×10^{-4}
Total	8.5×10^{-2}	2.8×10^{-2}

Table 74 Material requirements for onshore and offshore wind turbines.

a. [71].

Current HEP (£M/GWa) – Onshore Wind	Immediate Impacts		Delayed Impacts		Abnormal Impacts
	Occupational	Public	Occupational	Public[a]	
Extraction	-	-	-	-	-
Preparation	-	-	-	-	-
Generation	0.324 – 10.9	0 – 5.74	-	-	-
Reprocessing	-	-	-	-	-
Waste Storage and Disposal	-	-	-	-	-
Materials	0.224 – 0.952	-	-	0.769 – 4.47	-
Transport	0.003 – 0.086	0.006 – 0.153	-	-	-
Total	0.551 – 11.9	0.006 – 5.89	-	0.769 – 4.47	-

Table 75 Current onshore wind hazard elimination premiums for various impacts arising at different fuel chain stages.

a. Delayed public impacts are due to pollution, arising from exposures to particulate matter.

Incremental HEP (£M/GWa) – Onshore Wind	**Immediate Impacts**		**Delayed Impacts**		**Abnormal Impacts**
	Occupational	**Public**	**Occupational[a]**	**Public[b]**	
Extraction	-	-	-	-	-
Preparation	-	-	-	-	-
Generation	0.324 – 11.0	0 – 5.74	-	-	-
Reprocessing	-	-	-	-	-
Waste Storage and Disposal	-	-	-	-	-
Materials	0.214 – 0.933	-	0 – 0.015[c]	0.933 – 5.43	0.004 – 0.005[d,e]
Transport	0.008 – 0.222	0.011 – 0.287	-	0.110 – 0.640	-
Total	0.546 – 12.2	0.011 – 6.03	0 – 0.015	1.04 – 6.07	0.004 – 0.005

Table 76 Incremental onshore wind hazard elimination premiums for various impacts arising at different fuel chain stages.

a. Delayed occupational impacts are due to dust, except where otherwise indicated.
b. Delayed public impacts are due to pollution, arising from exposures to particulate matter.
c. Less than 1% due to radiation.
d. All resulting in immediate occupational impacts.
e. 6% is a financial HEP resulting from the environmental cost of coal, gas and oil accidents.

Current HEP (£M/GWa) – Offshore Wind	Immediate Impacts		Delayed Impacts		Abnormal Impacts
	Occupational	Public	Occupational	Public[a]	
Extraction	-	-	-	-	-
Preparation	-	-	-	-	-
Generation	0.005 – 19.7	-	-	-	-
Reprocessing	-	-	-	-	-
Waste Storage and Disposal	-	-	-	-	-
Materials	0.262 – 1.124	-	-	0.011 – 0.067	-
Transport	0.001 – 0.028	0.003 – 0.089	-	-	-
Total	0.267 – 20.8	0.001 – 0.030	-	0.011 – 0.067	-

Table 77 Current offshore wind hazard elimination premiums for various impacts arising at different fuel chain stages.

a. Delayed public impacts are due to pollution, arising from exposures to particulate matter.

Incremental HEP (£M/GWa) – Offshore Wind	**Immediate Impacts**		**Delayed Impacts**		**Abnormal Impacts**
	Occupational	**Public**	**Occupational**[a]	**Public**[b]	
Extraction	-	-	-	-	-
Preparation	-	-	-	-	-
Generation	0.009 – 19.8	-	-	-	-
Reprocessing	-	-	-	-	-
Waste Storage and Disposal	-	-	-	-	-
Materials	0.244 – 1.06	-	0 – 0.016[c]	0.425 – 2.47	0.005[d, e]
Transport	0.007 – 0.200	0.007 – 0.209	-	0.098 – 0.569	-
Total	0.260 – 21.1	0.007 – 0.209	0 – 0.016	0.523 – 3.04	0.005

Table 78 Incremental offshore wind hazard elimination premiums for various impacts arising at different fuel chain stages.

a. Delayed occupational impacts are due to dust, except where otherwise indicated.
b. Delayed public impacts are due to pollution, arising from exposures to particulate matter.
c. Less than 1% due to radiation.
d. All resulting in immediate occupational impacts.
e. 8% is a financial HEP resulting from the environmental cost of coal, gas and oil accidents.

Chapter 18 Comparative Analysis

18.1 Presentation of Results

The mortality risks associated with the generation of electricity by nuclear, coal, natural gas, onshore wind and offshore wind have been presented in chapters 15 to 17. The risks are delineated according to whether they are to the public or whether they are occupational. Risks are also separated according to whether they result in immediate fatalities or whether they result in delayed fatalities. Risks from abnormal operation (i.e. major accidents) are also treated separately because they may be particularly relevant to issues of social acceptability. Included with the assessment of mortality risks from severe accidents is a nominal assessment of the environmental damage, presented in terms of the maximum reasonable remediation cost. A distinction has also been made between the impacts resulting from currently operational facilities, and the impacts resulting from new build. The present value of the currently operational facilities, summed over the period from 2010 – 2070 are termed "current impacts", while the additional impacts from new build (which include construction and the use of materials) have been termed "incremental impacts". Although both impacts are important when comparing risks, the incremental impacts are arguably the more important figures, as they provide information on how the risks posed by the next set of power plants to be built compare with each other. The difference in magnitude between the current impacts and incremental impacts is also useful, as it gives a measure of "risk efficiency" - that is, what kind of improvements in the risk levels the new build plants offer over the existing plants.

The impacts have been assessed in terms of the loss of life expectancy, which was then monetised by using the J-value method presented in part 1, to give a "social cost" or "external cost" of risk. These costs are the maximum reasonable values to pay to completely eliminate the risk, were it possible to do so. For convenience, these costs were termed the "hazard elimination premiums", or HEPs. The environmental costs associated with major accidents are termed "financial HEPs". The HEPs for the various electricity generating technologies have been assessed at each stage of the fuel chain. The relevant data and summaries of the results are presented in the tables following each of the chapters. In this section the results of the risk analyses of the nuclear, fossil and renewable chains will be compared and contrasted.

The risks from the generation of nuclear, coal, gas, onshore wind and offshore wind summed over the whole fuel chain are presented in Table 79 for current risks. Table 80 presents the results for incremental risks. The impacts are shown disaggregated in terms of immediate occupational and public impacts, delayed occupational and public impacts, and impacts from abnormal operation. The results are aggregated to give indicative values in Table 81, Table 82. A figure for "total risk" in which all impacts are aggregated, is shown in Table 83, although care must be taken in interpreting these results, since some of the base data have large uncertainties associated with them. Moreover, a single index of detriment must subsume, inevitably, many different types of risk that may have different levels of acceptability for different individuals. That said, the J-value method provides an objective estimate of average risk valuation, based on documented actuarial statistics and the economic choices of the average individual in the nation. In comparing aggregated risk measures, the incremental risks used as the preferred measure of risk. As has been mentioned, these are arguably the more important measure as they allow the choices regarding how to optimise future electricity generating systems to be assessed. The incremental impacts are also shown graphically at the end of this chapter, from Figure 30 to Figure 40.

The comparisons of these results are discussed below. A HEP of £0.5M/GWa was judged to be the region below which risks become less significant, which corresponds to around 0.1 fatalities per GWa, as is used by Ball et al (1998) [15].

18.2 Immediate Occupational Impacts

Nuclear and gas power are estimated to have the lowest risks of immediate fatalities to their workforce. For current risks, the gas impacts are below the £0.5M/GWa threshold, indicating that these risks are less significant. The upper end of all the other estimates, for both current and incremental risks, lies above this threshold, although for nuclear and incremental gas impacts, the high end is only slightly over this threshold. The risks from coal and both wind technologies are more significant, although the ranges are wide, particularly for the wind technologies. This large uncertainty is due to the currently low observed number of fatalities associated with wind energy coupled with the relatively small output provided by these technologies. Data on fatalities will become more reliable with increasing rates of construction of wind turbines onshore and offshore (where conditions may suggest higher risks). Large-scale wind power is also a comparatively recent industry when compared with the other technologies. There is therefore more scope for reductions in these risks than there is for coal, gas and nuclear. The high risks estimated for coal power are mainly due to mining fatalities, although again there is uncertainty in the numbers used arising from assumptions about the source of the coal and associated safety levels.

The orderings of impacts are broadly preserved for current and incremental risks. Nuclear is the only technology in which the incremental impacts are smaller than the current impacts. Coal and both wind technologies have incremental and current impacts that are the same, whilst gas has incremental impacts that are greater than current impacts, although the increase is small.

18.3 Immediate Public Impacts

Immediate public impacts are primarily due to transport accidents. These risks are generally very small for each technology, with the exception of onshore wind. Although the low end of the risk estimate for onshore wind is small, the high end is relatively large. This is due to the attribution of risks to the public from the operation of wind turbines. As was discussed in section 17.3, this risk from this source is highly uncertain due to the fact that no public fatalities from wind power generation have been observed in the UK. The risk estimates were determined from Poisson statistics, and were found to be comparable with the public fatalities observed during this period in Canada, where the onshore wind power profile is similar to the UK, which validates the UK estimate, although the large uncertainty must be noted.

Amongst the other technologies, the greatest impacts arise from coal and offshore wind, although even the high end of these impacts is still below the £0.5M/GWa threshold. All technologies have incremental impacts that are slightly greater than their current impacts. These differences are fairly small however. This means that expansion of any of these technologies would not greatly affect the risk of immediate public fatalities, on a per GWa basis. On an absolute basis, the number of public fatalities would be expected to increase linearly with the amount of electricity generated.

18.4 Delayed Occupational Impacts

Delayed occupational risks are generally relatively small. For all generation technologies, except nuclear, the primary delayed occupational risk is dust exposure, which can cause pneumoconiosis. For nuclear power the main delayed occupational risk comes from ionising radiation, which can cause cancer.

The only significant delayed, occupational risk arises in coal power, due to dust exposure to workers in coal mines, leading to pneumoconiosis. The methods for estimating this impact is discussed in Appendix C. The method, which was originally used by Ferguson (1989) [83], is based on an extrapolation of the trend in loss of life expectancy currently observed for present fatalities resulting from exposures from a few decades ago forward towards a point in time where the mean age of death of coal worker's pneumoconiosis sufferers is equal to future mean age of the present workforce, which will be about 40 years from now. The limitations of this method are discussed in section 16.3. The uncertainties are quite large, and the upper end may be an overestimate. It may even be a gross overestimate if opencast mining practices become preferred to deep mining.

The next greatest delayed occupational impact arises in nuclear power as a result of exposures to radiation at all stages of the fuel chain. These impacts are not above the £0.5M/GWa threshold and are therefore not judged to be significant. In addition, nuclear is the only technology that has incremental delayed occupational risks smaller than the current risks. This is because the new build are more "risk efficient", in that they can produce more output than the current plants without an associated increase in doses to the workforce. The current and incremental impacts from coal remain the same, whilst the incremental impacts from gas and both wind technologies are greater than the current impacts, although the increase in fairly small and is not a significant risk.

18.5 Delayed Public Impacts

It is striking that all the generating technologies considered produce delayed public impacts and that, contrary to some perceptions, nuclear power produces the lowest delayed impacts to the public. In fact, for incremental risks, nuclear power is the only technology which does not have an impact above the threshold at which risks are judged to become more significant. By far the greatest impact is from coal power, which is due to particulate emissions. The incremental impacts are smaller than the current impacts, due to the improvement in the emission rate of particulate matter. The resulting impacts will still be the largest out of all the technologies, however. It should be noted that the potential impacts from emissions of toxic substances in the burning of coal are difficult to quantify and have thus not been explicitly considered here. This may lead to an underestimate of health effects due to coal emissions.

Both wind technologies also present delayed risks to the public, and this is because of the large quantities of materials required. For onshore wind, both current and incremental impacts are significant. For offshore wind, however, only the incremental impacts are significant, whilst the current impacts are the lowest of all the technologies and well below the threshold at which risks become more significant. Both wind technologies have greater incremental impacts than current impacts, indicating that expansion of this technology will result in more risk per GWa than is currently being experienced.

Natural gas has the second highest current public delayed impacts after coal. This is due to the particulate emissions from the current plants. However, the incremental impacts are much smaller, as the new build have little emissions of particulate matter. The incremental impacts are the second lowest, after nuclear. The risk efficiency of new gas plants is therefore very good.

Nuclear power generally presents small public delayed impacts, most of which are from collective radiation dose. However, these estimates are only applicable to exposures to the UK population. If exposures to Europe or over the world were taken, then the impacts would rise above this threshold. However, as has already been repeatedly mentioned, such calculations involve summing small doses over large populations and over long time periods. The results are therefore quite speculative and must be viewed with caution. The results can be given more realism by introducing "cut-off" doses, whereby all exposures below a certain level are discounted from the calculation. The results of using different regions for the collective dose calculation, and if applying these cut-off doses, are presented and discussed in chapter 19. In the most pessimistic case, the public delayed impacts increase by a factor of about 40, making them slightly higher than the gas estimate, and comparable to onshore wind.

18.6 Impacts Resulting from Abnormal Operation

The estimates suggest that the impacts from major accidents from the two wind chains and the nuclear chain are similar, and very small. The major impacts in the wind chains occur at the extraction stage of the construction materials chain. These major impacts involve immediate risks to the workforce. For nuclear, the impacts are mostly to members of the public through delayed risk associated with radiation exposure. As discussed above, nuclear risk estimates are derived from a probabilistic risk analysis (PRA) of the AP1000 reactor. PRA techniques generally represent the best data that can be used in assessing the risks from new generation nuclear plants, but until there have been many operational reactor years of these plants, there will be very little data even from the extrapolation of estimates from actual accident precursor frequencies. Greater abnormal risks are found in the gas chain, although the estimates are below the £0.5M/GWa threshold at which risks are judged to become more significant. The greatest risks are due to large coal accidents, which are slightly greater than the gas risks, and just over the threshold of £0.5M/GWa. There is little difference between the current and incremental impacts.

18.7 Aggregated Measures of Risk

Measures of total risk involve aggregation of diverse sources of risk. The acceptability of such aggregation is questionable. For example, the impacts from radiation may be much more important for some individuals than impacts of routine accidents, and so adding the two together may be seen as being misleading. Nevertheless, the J-value framework offers the ability to convert all sources of risk into a monetary figure, providing a rationale for aggregating such impacts. Measures of total risk can therefore be calculated and compared. The dimensions that can be compared are immediate and delayed risks, occupational and public risks, and total risks. One other dimension is the comparison of normal and abnormal risks, however, as has just been discussed, abnormal impacts are generally much lower than impacts due to normal operation, and so these will not be discussed further here. The results are shown in Table 81, Table 82 and Table 83. Here, only the incremental results will be discussed, as these are the most relevant figures for comparing the effects of choices regarding future electricity generating systems. These are also shown in the figures at the end of this chapter, from Figure 30 to Figure 40.

The aggregated impacts tend to be dominated by the public delayed impacts resulting from pollution. This means that delayed risks are generally greater than immediate risks, and that public risks are greater than occupational risks. However, this is not the case for the wind technologies, where the immediate impacts are greater than the delayed impacts, and where the occupational impacts are about the same order of magnitude as the public impacts, due to the wide uncertainty in the risks of constructing and operating wind turbines. Coal technology poses the highest delayed risk and the highest public risk. Gas, onshore wind and offshore wind present medium impacts for delayed risk and public risk. For immediate risks, coal, onshore wind and offshore wind are all similar, with the wind technologies being slightly higher. The same is true for occupational risks. Gas and nuclear both present the lowest occupational and immediate risks, whilst for public risk and delayed risk, nuclear presents considerably less risks than any other of the assessed technologies.

In terms of total risk, the results show three distinct cases: coal presents considerably higher risks than any of the other technologies. Gas, onshore wind and offshore wind present medium risks, while nuclear presents the lowest risk. For current and incremental impacts, the coal, gas and nuclear technologies all have smaller incremental impacts than current impacts. This indicates that the new build stations are more "risk efficient", in that more output can be produced without a proportional rise in risk. Onshore wind incremental impacts are similar to the current impacts, so that there is no change in the risk efficiency. Offshore wind incremental impacts are greater than the current impacts, however, which mean that the new facilities pose more risk per unit electricity than the existing plants.

Current Impacts - Summary (£M/GWa)	Normal Operation				Abnormal Operation
	Immediate Impacts		Delayed Impacts		
	Occupational	Public	Occupational[a]	Public[b]	
Nuclear	0.032 – 1.27	0 – 0.010	0.244 – 0.292[c]	0.231 – 0.773[d]	0.007[e,f]
Coal	0.596 – 3.83	0.002 – 0.086	0.009 – 2.40	69.8 – 406	0.658 – 0.808[g]
Gas	0.038 – 0.483	0 – 0.009	negligible	9.12 – 53.1	0.115 – 0.142[g]
Onshore Wind	0.551 – 11.9	0.006 – 5.89	-	0.769 – 4.47	-
Offshore Wind	0.267 – 20.8	0.001 – 0.030	-	0.011 – 0.067	-

Table 79 Summary of current impacts from each technology.

a. Delayed occupational impacts are mainly due to dust, except where otherwise indicated.
b. Delayed public impacts are mainly due to pollution, except where otherwise indicated.
c. Impacts mainly due to radiation.
d. To determine European region impact, multiply by 8.77. To determine world impacts, multiply by 80.24.
e. Mainly delayed public impacts, less than 1% immediate occupational impacts.
f. About 30% is a financial HEP, resulting from environmental impacts.
g. Immediate occupational impacts.

Incremental Impacts - Summary (£M/GWa)	Normal Operation				Abnormal Operation
	Immediate Impacts		Delayed Impacts		
	Occupational	Public	Occupational[a]	Public[b]	
Nuclear	0.011 – 0.561	0.001 – 0.013	0.051 – 0.067[c]	0.063 – 0.148[d]	0.007 – 0.008[e,f]
Coal	0.582 – 4.09	0.004 – 0.156	0.002 – 2.40	52.8 – 307	0.670 – 0.821[g]
Gas	0.049 – 0.560	0.001 – 0.024	0.006 – 0.007	0.848 – 1.39	0.116 – 0.143[g]
Onshore Wind	0.546 – 12.2	0.011 – 6.03	0 – 0.015	1.04 – 6.07	0.004 – 0.005[g]
Offshore Wind	0.260 – 21.1	0.007 – 0.209	0 – 0.016	0.523 – 3.04	0.005[f]

Table 80 Summary of incremental impacts from each technology.

a. Delayed occupational impacts are mainly due to dust, except where otherwise indicated.
b. Delayed public impacts are mainly due to pollution, except where otherwise indicated.
c. Impacts mainly due to radiation.
d. To determine European region impact, multiply by 8.77. To determine world impacts, multiply by 80.24.
e. Mainly delayed public impacts, less than 1% immediate occupational impacts.
f. About 30% is a financial HEP, resulting from environmental impacts.
g. Immediate occupational impacts.

Current Impacts - Summary (£M/GWa)	**All Immediate Impacts**	**All Delayed Impacts**	**All Occupational Impacts**	**All Public Impacts**
Nuclear	0.033 – 1.28	0.475 – 1.07 (0.007)	0.277 – 1.56	0.231 – 0.783 (0.007)
Coal	0.598 – 3.91 (0.658 – 0.808)	69.8 – 408	0.605 – 6.22 (0.658 – 0.808)	69.8 – 406
Gas	0.038 – 0.499 (0.115 – 0.142)	9.12 – 53.1	0.038 – 0.483 (0.115 – 0.142)	9.12 – 53.1
Onshore Wind	0.557 – 17.8	0.769 – 4.47	0.551 – 11.9	0.775 – 10.4
Offshore Wind	0.268 – 20.8	0.011 -0.067	0.267 – 20.8	0.012 – 96.0

Table 81 Summary of current of risks from each technology, aggregated by impact categories. Impacts are due to normal operation. Impacts from abnormal operation are shown in brackets.

Incremental Impacts - Summary (£M/GWa)	**All Immediate Impacts**	**All Delayed Impacts**	**All Occupational Impacts**	**All Public Impacts**
Nuclear	0.012 – 0.574	0.113 – 0.216 (0.007 – 0.008)	0.062 – 0.628	0.063 – 0.161 (0.007 – 0.008)
Coal	0.587 – 4.25 (0.670 – 0.821)	52.8 – 309	0.585 – 6.49 (0.670 – 0.821)	52.8 - 307
Gas	0.050 – 0.584 (0.116 – 0.143)	0.854 – 1.40	0.055 – 0.567 (0.116 – 0.143)	0.849 – 1.42
Onshore Wind	0.557 – 18.2 (0.004 – 0.005)	1.04 – 6.04	0.546 – 12.2 (0.004 – 0.005)	1.05 – 12.1
Offshore Wind	0.268 – 21.3 (0.005)	0.523 – 3.06	0.260 – 21.1 (0.005)	0.530 – 3.25

Table 82 Summary of incremental risks from each technology, aggregated by impact categories. Impacts are due to normal operation. Impacts from abnormal operation are shown in brackets.

Total Impacts – Summary (£M/GWa)	**Total Current Impacts**	**Total Incremental Impacts**
Nuclear	0.508 – 2.34 (0.007)	0.125 – 0.789 (0.007 – 0.008)
Coal	70.4 – 412 (0.658 – 0.808)	53.3 – 313 (0.670 – 0.821)
Gas	9.16 – 53.6 (0.115 – 0.142)	0.904 – 1.98 (0.116 – 0.143)
Onshore Wind	1.33 – 22.3	1.60 – 24.3 (0.004 -0.005)
Offshore Wind	0.280 – 20.9	0.790 – 24.3 (0.005)

Table 83 Summary of total current and incremental risk, aggregated over each impact category. Impacts are due to normal operation. Impacts from abnormal operation are shown in brackets.

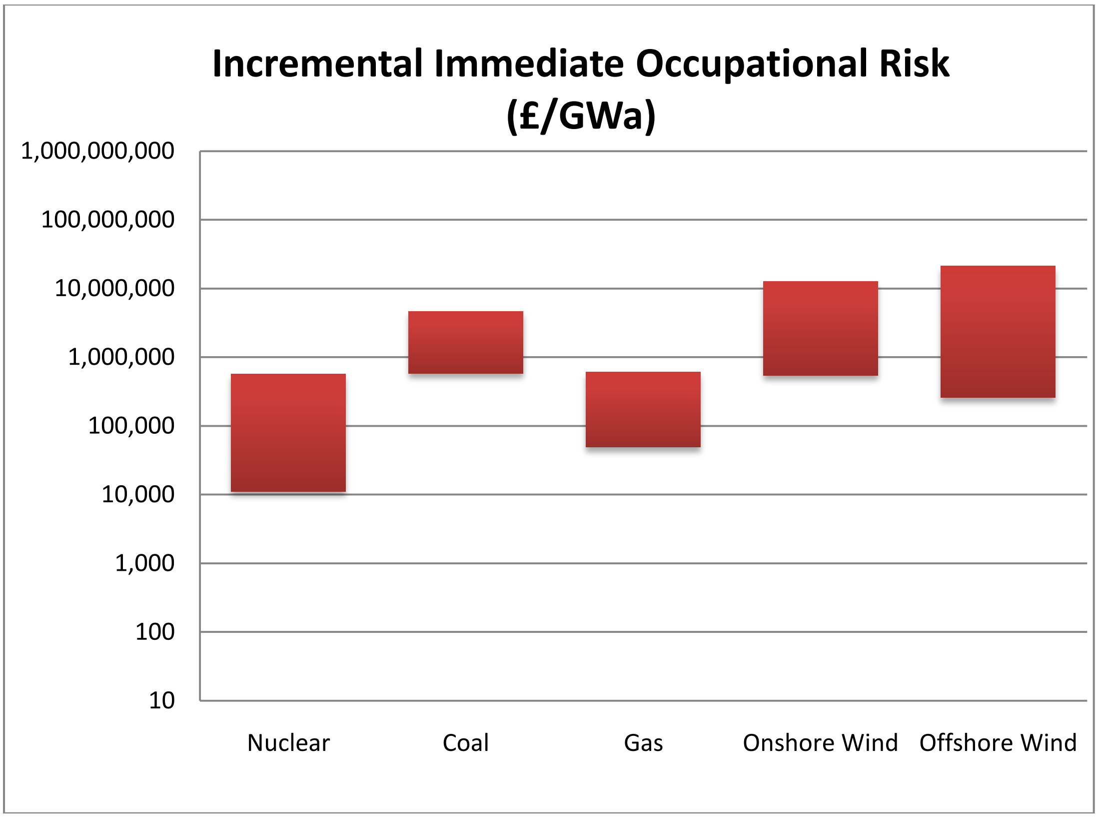

Figure 30 Incremental immediate occupational risks for each technology.

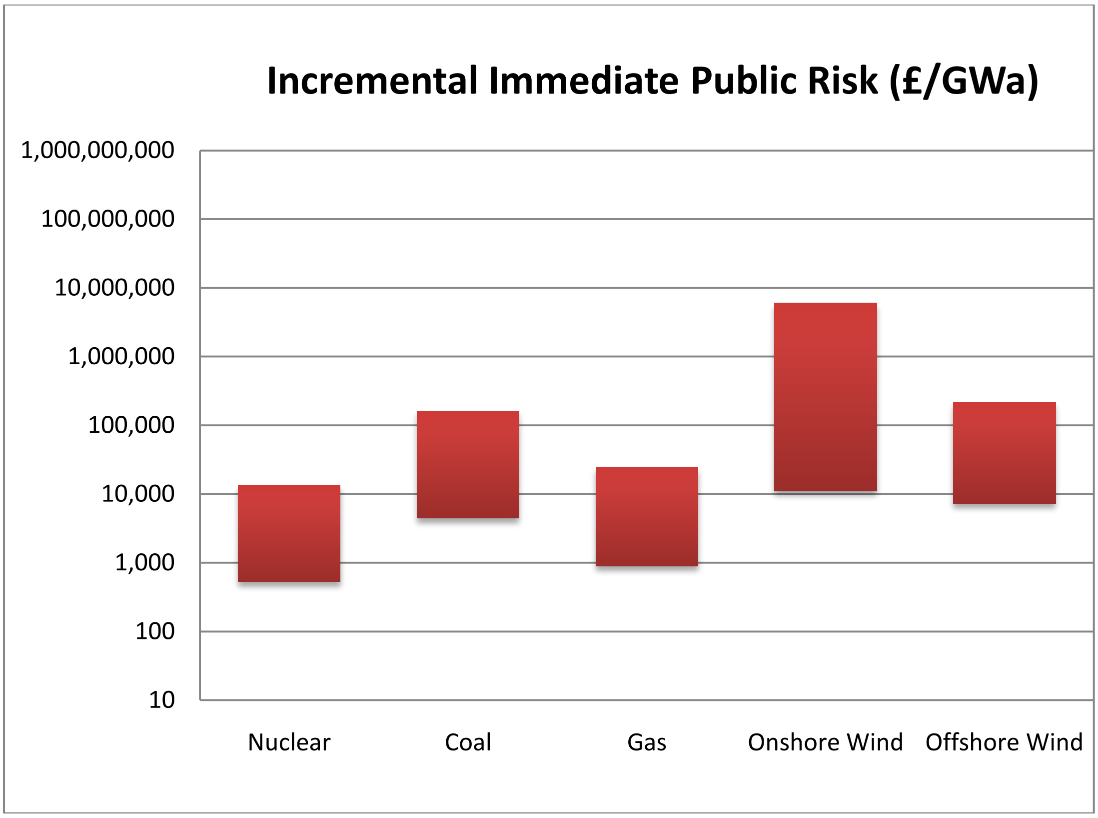

Figure 31 Incremental immediate public risks for each technology.

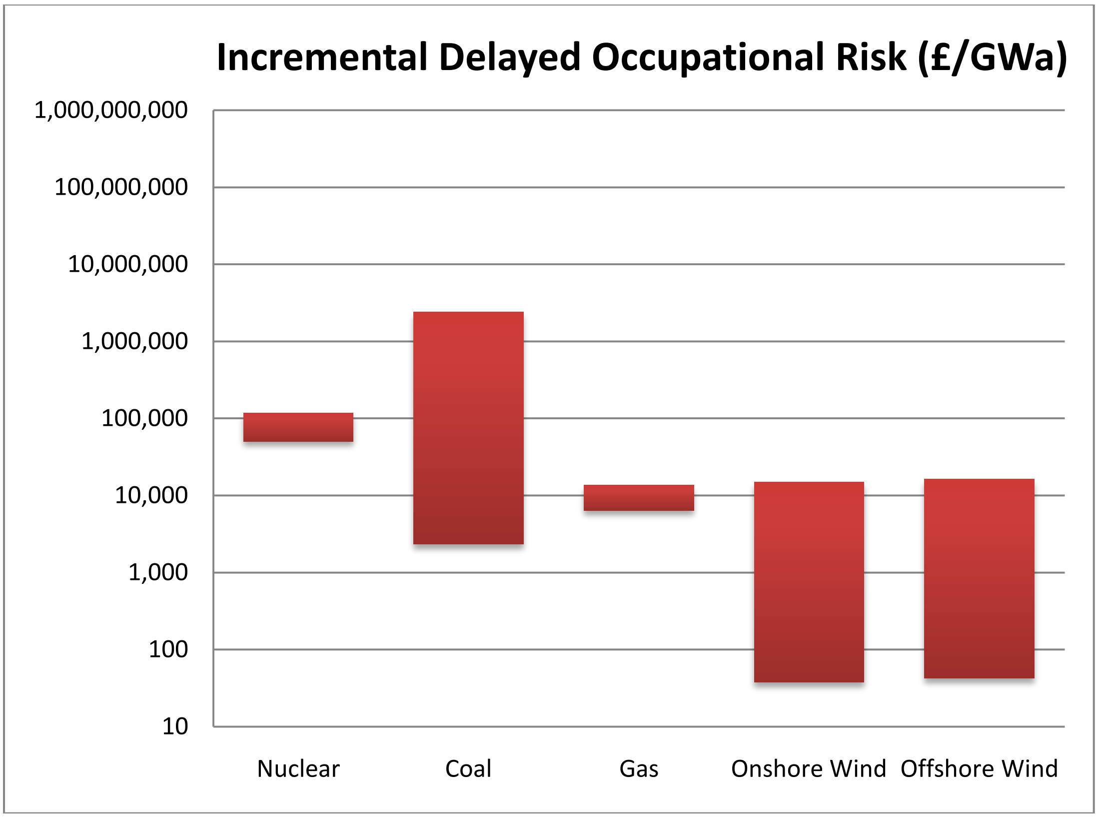

Figure 32 Incremental delayed occupational risks for each technology.

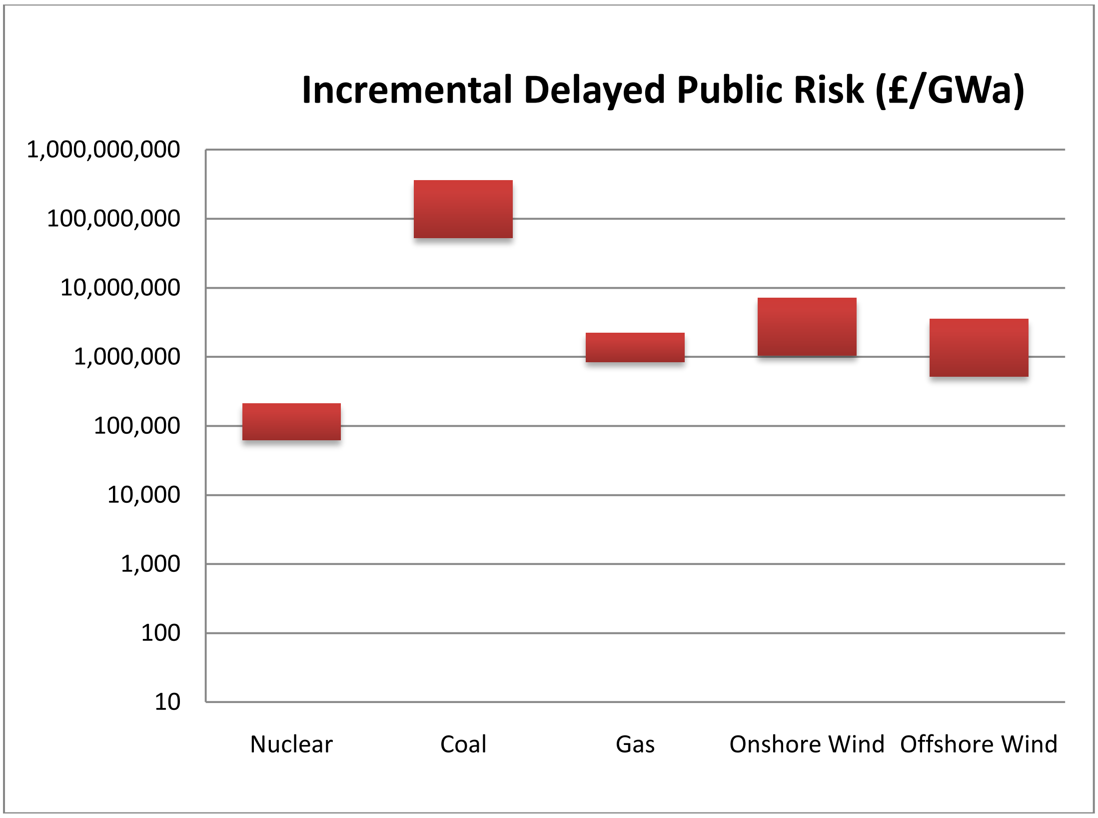

Figure 33 Incremental delayed public risks for each technology.

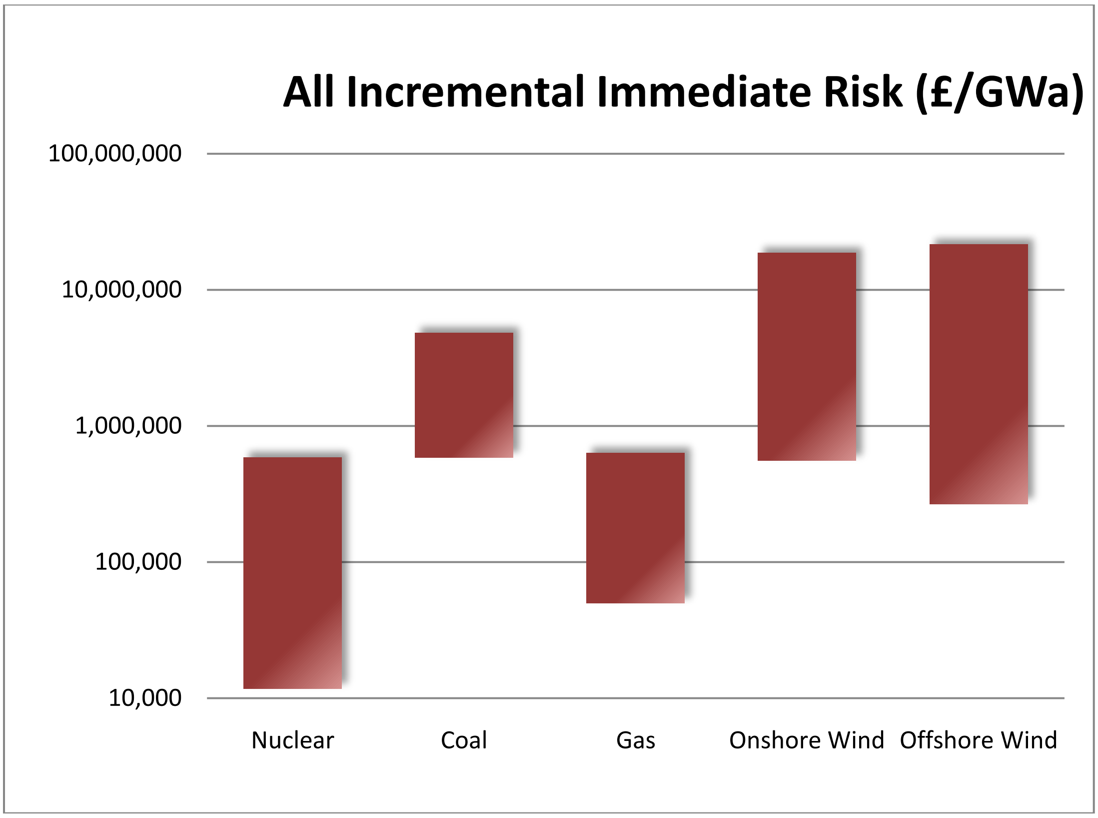

Figure 34 All incremental immediate risk for each technology.

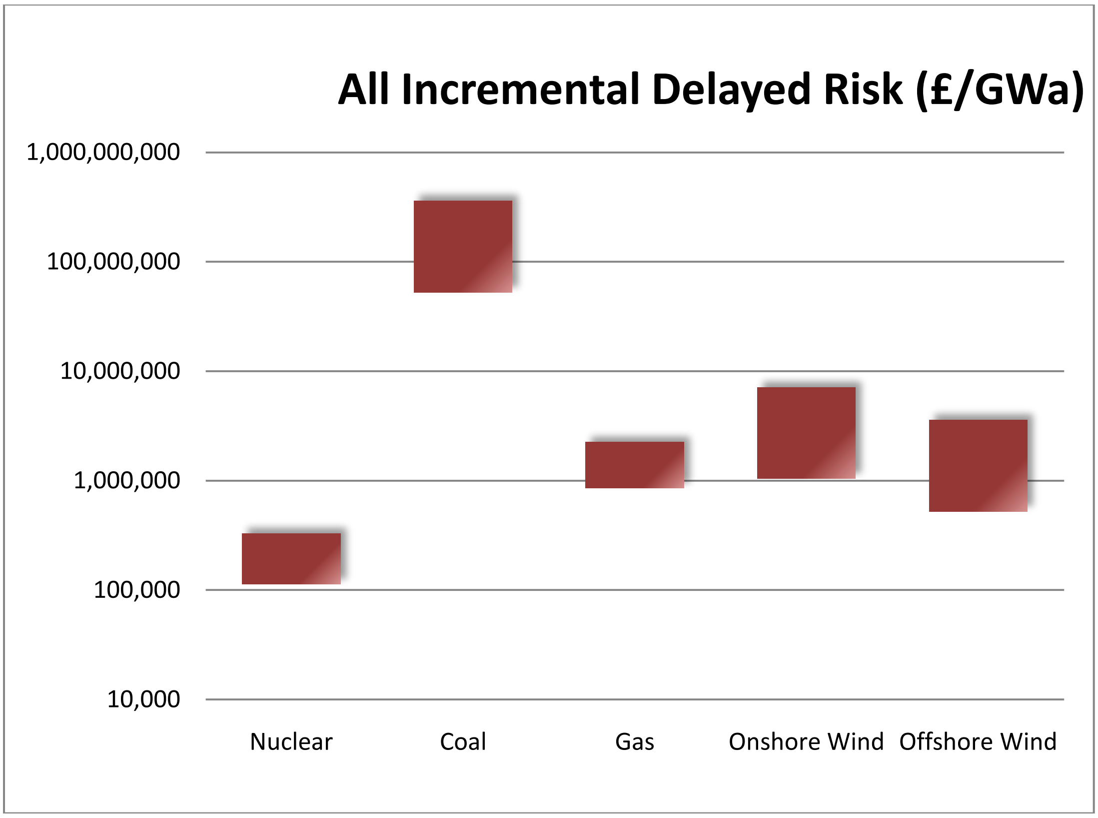

Figure 35 All incremental delayed risk for each technology.

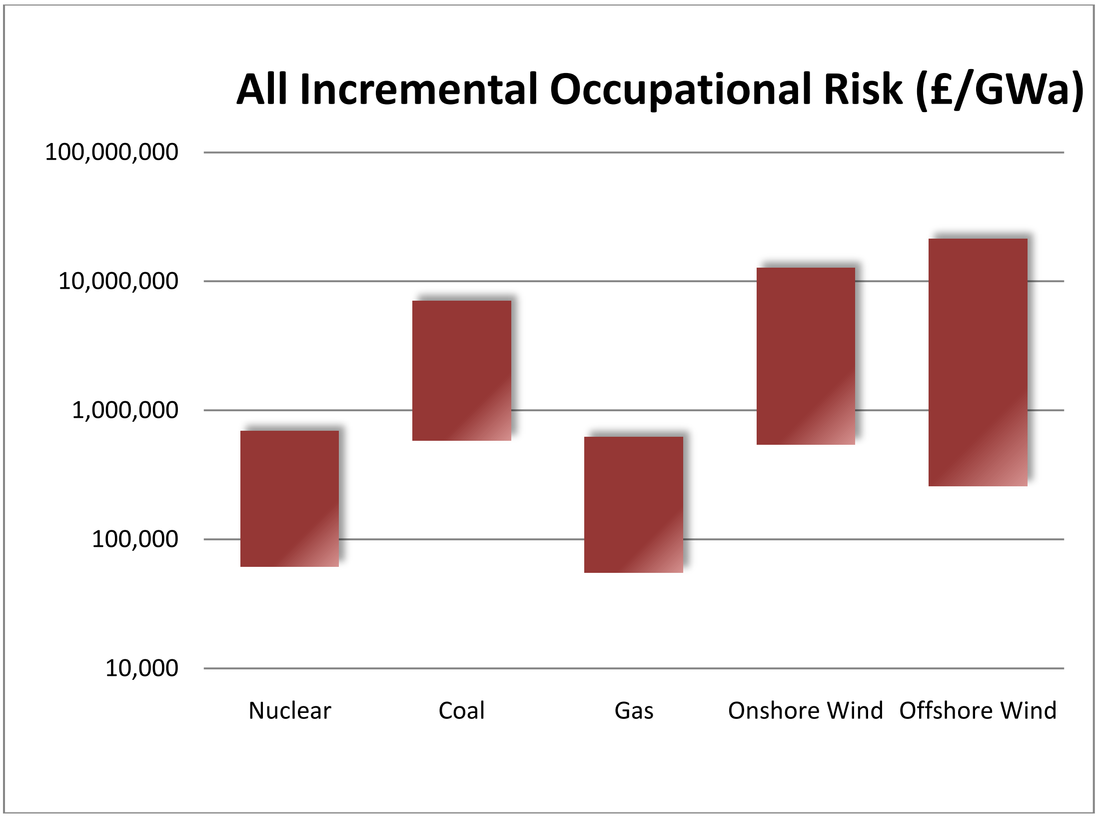

Figure 36 All incremental occupational risk for each technology.

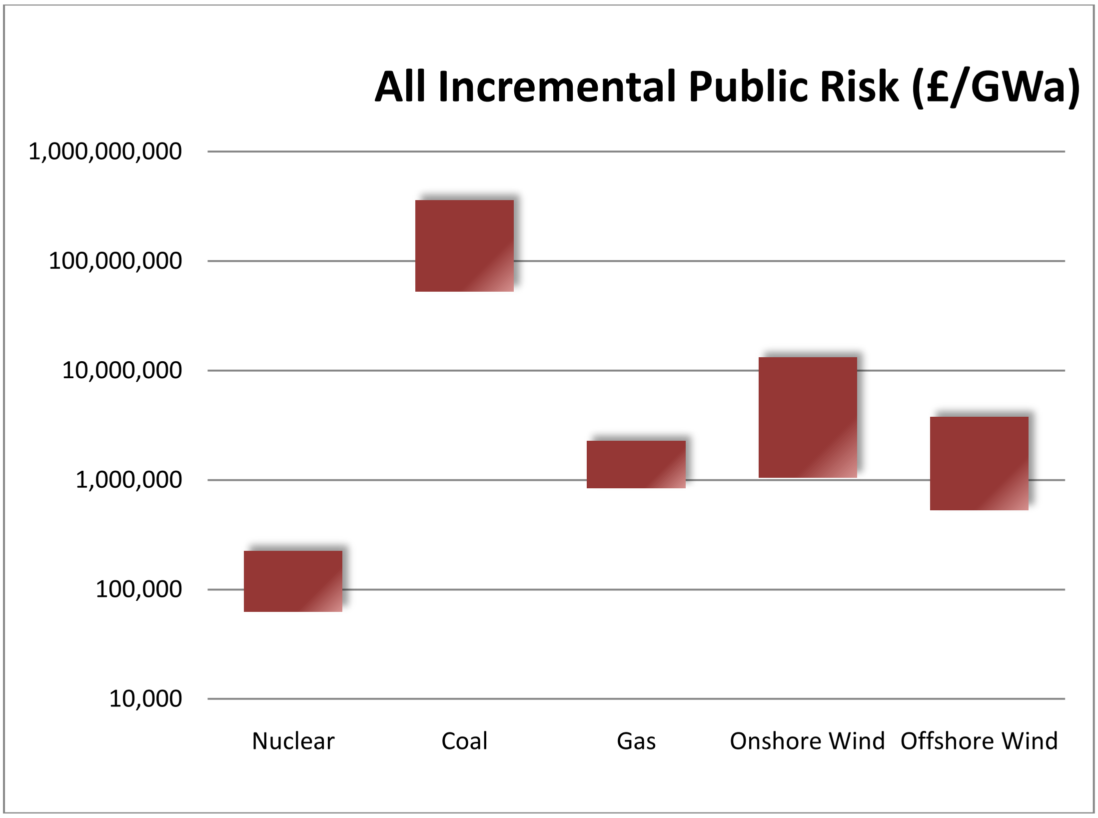

Figure 37 All incremental public risk for each technology.

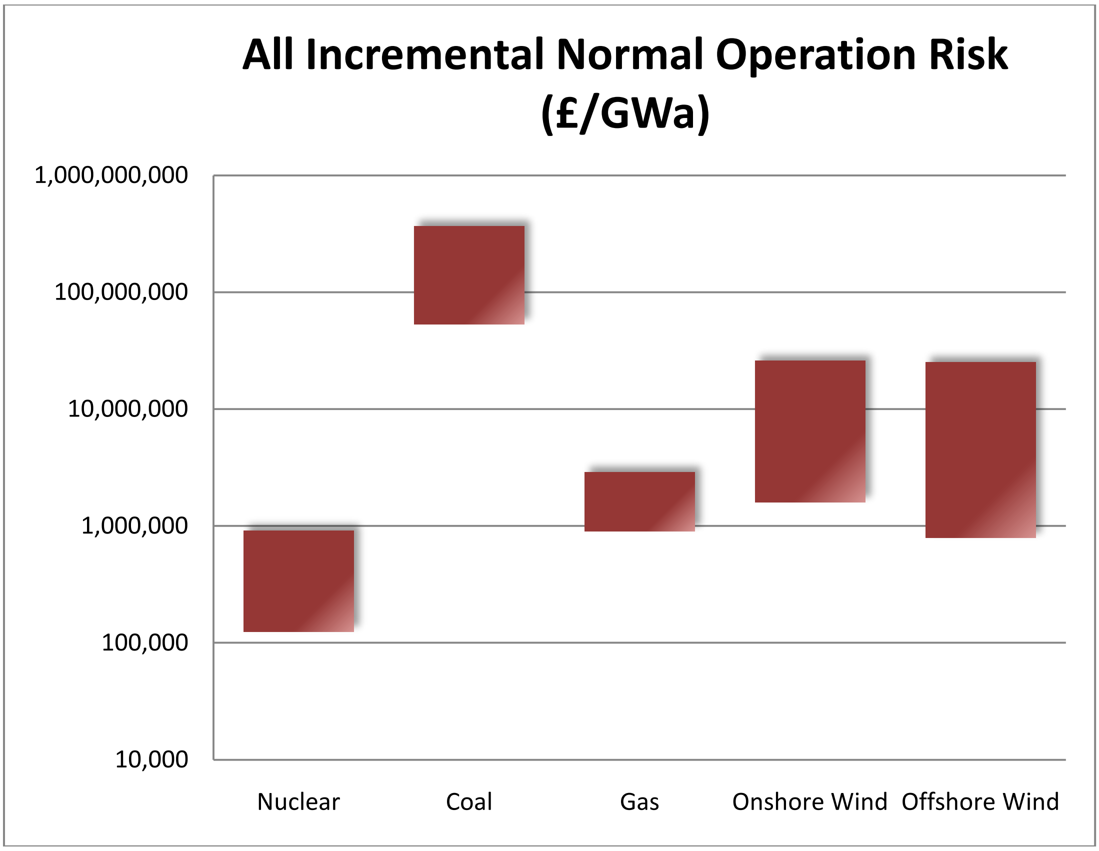

Figure 38 All incremental normal operation risk for each technology.

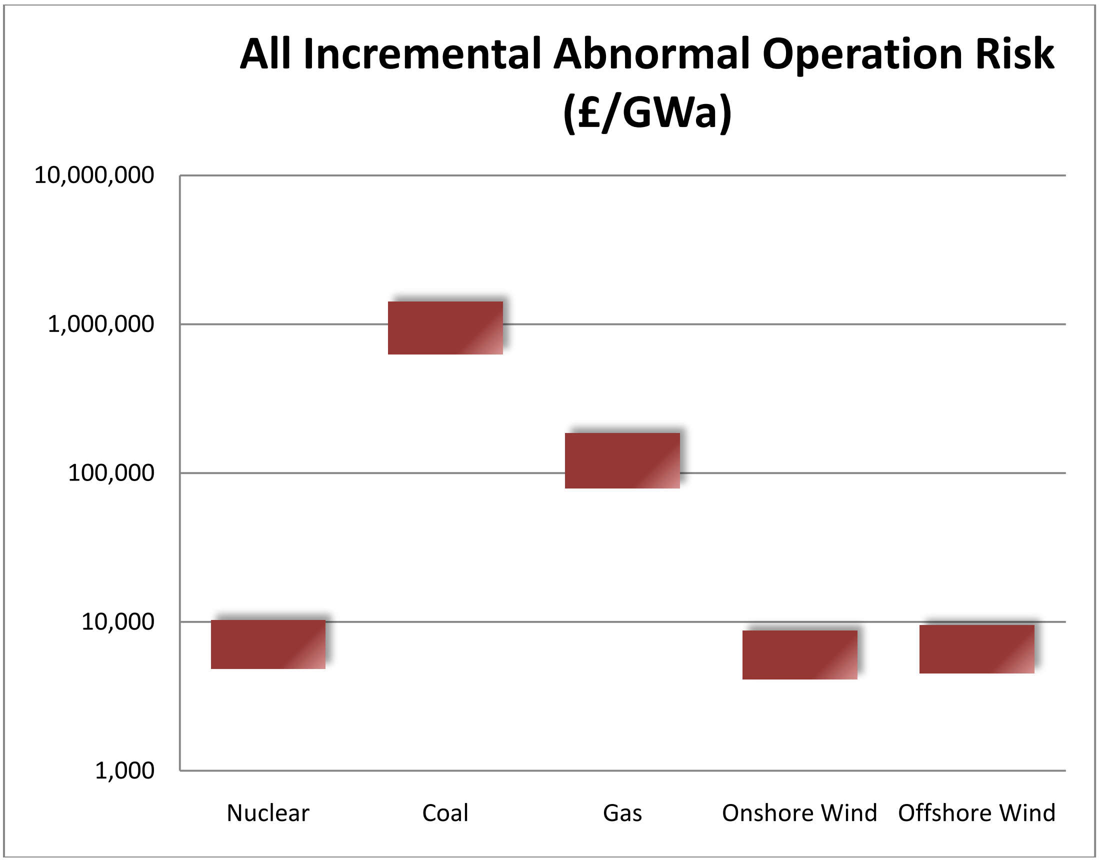

Figure 39 All incremental abnormal operation risk for each technology.

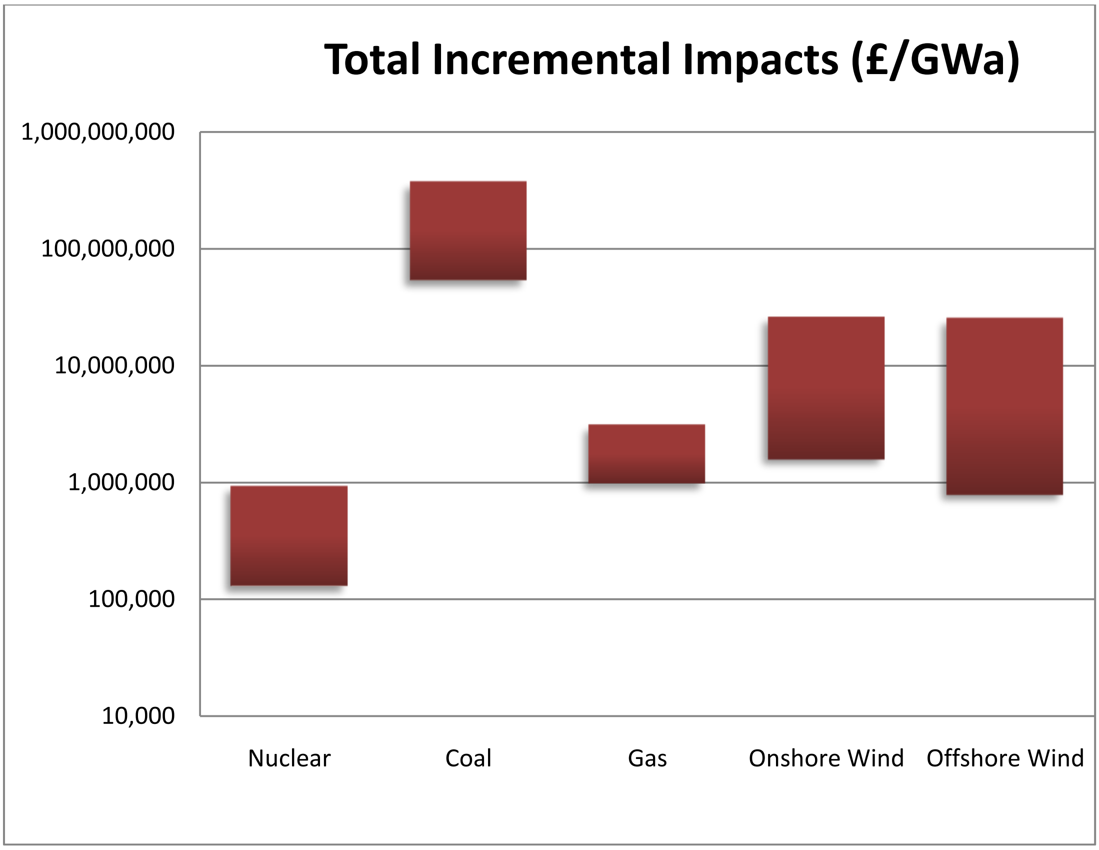

Figure 40 Total incremental risk for each technology.

Chapter 19 Discussion

19.1 Sensitivity Analysis

A preliminary sensitivity analysis of the results of the comparative analysis can be performed by visually inspecting the distributions of the total impacts across the fuel chain stages and across the assessed dimensions of risk. Further assessment of the robustness of the results can be determined by testing their sensitivity to the underlying assumptions used in deriving them. There are a number of assumptions that can be tested, but the most relevant ones that will be discussed here are the assumptions regarding the treatment of public collective doses and coal mining statistics.

The distribution of the total impacts throughout the various stages of the fuel chain for each technology is shown in Figure 41. For nuclear, coal, onshore wind and offshore wind, the generation stage is the dominant contributor to the total impacts. For coal, this stage is responsible for almost all of the risk, comprising over 95% of the total. This is primarily due to the pollution emissions, which are associated with large impacts. For nuclear, many of the other stages also contribute significantly to the total risk. The generation stage contributes about 55% of the total, whilst the extraction, preparation, reprocessing and transport stages each contribute 10%. The materials stage contributes the remaining 5%. The share of the waste storage and disposal chain in the total is negligible. Both wind technologies have similar distributions of impacts. For onshore and offshore wind, generation accounts for 66% and 79% respectively. Materials account for 30% and 17%, while transport accounts for around 5% for both technologies. Natural gas is the only technology where impacts from the generation stage don't contribute the majority of all the impacts. Instead, the main source of risk for natural gas is from the construction materials chain, which accounts for 73% of the total. This is followed by the extraction stage, which contributes 13%. The generation stage accounts for 8% of the total, and transportation accounts for 5%. The materials risk is dominated by pollution emissions in the manufacture of steel and concrete. This analysis also provides information about how direct the risks are. Impacts from the construction materials may be regarded by some as being too indirect and not specific enough to the electricity generating process to warrant inclusion in the analysis. If these indirect impacts were excluded, natural gas impacts would be 23% of their present value (transportation is also counted as an indirect risk). Onshore and offshore wind impacts would be 66% and 79% of their initial impacts respectively. Nuclear would be 84% and coal would be 98% of initial impacts.

The distribution of the impacts across the dimensions of risk may also be assessed. Figure 42 shows how the impacts are distributed between public and occupational risk. Both coal and gas pose risks that are mainly to the public, whilst nuclear and offshore wind poses risks mainly to workers. Onshore wind has an even split between the two categories. Figure 43 shows risks distributed between immediate and delayed impacts. Coal and gas have impacts that are predominantly delayed impacts, while nuclear, onshore wind and offshore wind have mainly immediate impacts. Finally, Figure 44 shows how the risks are distributed between normal and abnormal impacts. Abnormal impacts account for only a small fraction of the total risk for all assessed generating systems. For coal and both wind technologies, this fraction is completely negligible. The proportion of abnormal risks for nuclear is 2%, whilst for gas it is 8%. As the environmental costs, as characterised by the financial HEP, is a small fraction of the total abnormal risks, they have very little overall effect on total impacts.

This preliminary analysis suggests that there are two types of impact that have a major effect on the overall risk profile. These are impacts resulting from particulate matter emission that lead to death, and impacts from immediate occupational fatalities. The particulate matter impacts can be seen to dominate the impacts from gas and coal, although for gas the impact occurs more indirectly in the materials chain. Both of these technologies are characterised by a high proportion of delayed impacts and public impacts, as well as the relevant stage of the fuel chain where the pollution is emitted being dominating the risk distribution. In contrast, nuclear and wind technologies have impacts that have a high proportion of occupational impacts and immediate impacts, as well as a dominant generation stage. These three technologies have had fairly low numbers of observed fatalities. This suggests that the effect of using Poisson statistics to assess the uncertainty may disproportionately affect these particular technologies. This is because low observed fatality counts necessarily have wide confidence limits. Some other way of incorporating uncertainty may be more appropriate, but this remains a topic for further research. It has already been discussed in section 5.9 that the assumed response of exposures to pollution may be inaccurate, and that fitting a better response function could be done for future work. It is possible that the assumed response, namely that there is an immediate relative increase in hazard rates that is constant for 15 years before stopping completely, results in overestimated impacts. This may mean that the coal and gas results are also overestimated. However, different response functions have been tested. Instead of assuming a constant relative risk for 15 years, durations of ten years, five years and one year were used instead. Coal impacts were the only ones that had a large change, dropping by about 50% in the latter, most conservative case when a response duration of one year is assumed. However, even in this case, the coal impacts are still the significantly greater than the other technologies. The overall ordering of the risk levels are unchanged by these modifications. Assuming a one year response duration is considered to be extremely conservative, as many studies have found there to be delayed effects from exposure to pollution that can last for many years, as was discussed in section 5.9. The initial duration of fifteen years may even be an underestimate, so that coal and gas impacts should actually be larger than they already are. Therefore, it seems likely that the current pollution estimates are robust.

Another assumption that can be tested to assess sensitivities is regarding the calculation of public collective doses over different regions. As has been mentioned, the delayed public risks from radiation emissions involved in nuclear power production are dependent upon the region over which the impacts are assessed. The results presented in Table 80 are for doses to the UK public, but this region can be extended to Europe or to the world. As was discussed in section 13.4, such impacts involve vanishingly small doses to a large number of people, which are calculated over a 500 year period. Any such detriment would be impossible to empirically detect, and the risk to any individual not in the immediate vicinity of the power plant would be negligible. Nevertheless, according to the traditionally used assumption that every additional impinging ionising particle increases the risk of premature death, the individually negligible risks can be summed up over billions of people to obtain a significant impact. When using the European region, the delayed incremental public risks from nuclear power increase from a HEP of around £0.1M/GWa to a HEP of £0.4-0.5M/GWa, which is still the lowest public delayed impacts of all five technologies. When using the world region, the impacts correspond to a HEP of £3.7-4.2M/GWa, slightly higher than gas and offshore wind impacts, and comparable to onshore wind impacts. These results can be given more realism by introducing cut-off doses; levels below which any such doses are ignored for being too small to produce any observable effects.

The results are highly sensitive to such cut-off levels. For example, a cut-off dose of 0.015 μSv corresponds to a reduction in life expectancy of about half a second, based on the linear no threshold model of radiation risk. Setting this as the cut-off level reduces the global impacts to a HEP of £0.2-0.3M/GWa. Setting the cut-off dose a factor of 10 higher, corresponding to a reduction in life expectancy of less than 10 seconds, will reduce the global impact to below the original levels based on the UK only.

Another issue tested for sensitivity are coal mining statistics. Much coal is imported from Russia and China, and the trend is towards ever higher levels of importation see DECC (2011g) [54]. It may therefore be appropriate to use these safety statistics for abnormal coal operation instead. If current Chinese safety statistics are used for coal extraction, then the estimate for the coal mining immediate occupational fatality impact increases by a factor of around 7. The risk from contracting pneumoconiosis in such mines is also likely to be larger, but data is not available for this. As the other technologies also rely on coal mining for their steel, the related risk also increases, but to a much lesser degree than for coal. The wind technologies immediate occupational fatality impact rises by about 2%, while the nuclear impact rises by about 3%. The gas impact changes by less than 1%. As well as affecting immediate occupational impacts, historical major accident data for China, see ExternE (2008b) [82] can also be used to estimate the risk of major coal accidents. This has a large effect on the abnormal impacts. For nuclear and gas, the impacts increase by a factor of 2.5 and 1.3 respectively. For both wind technologies, the impacts increase by a factor of 46, whilst for coal, the impacts increase by a factor of 48. For nuclear and gas, their respective shares of abnormal impacts in the total risk changes from 2% and 8% respectively, to 4% and 10% respectively. For both wind technologies, the share increases from practically 0% to 2%. For coal there is a large increase in the abnormal share, from almost 0% to 15% of the total. This suggests that the coal results are highly sensitive to the use of such statistics, the other technologies less so.

19.2 General Discussion

Although the public delayed impacts for nuclear power are sensitive to the timescales and region over which they are assessed, the change in impact between the UK and Europe region is small, with the impact remaining around the threshold at which risks become significant. If radioactive emissions are calculated over the global region, then the results increase substantially. However, when a cut-off dose level of 0.015 μSv (corresponding to a loss of life expectancy of half a second) is introduced, the impact is reduced to near UK-only levels.

A simplifying assumption used in the analysis above is that all life expectancy calculations are determined from UK statistics. Clearly, a more realistic calculation would use statistics appropriate to the region concerned. However, this assumption will give conservative results, in that they overestimate the effects, rather than underestimate them. The largest overestimation will be for nuclear power, in which some uranium mining statistics were based on Namibian data, where the life expectancy is lower than in the UK. Also, if the world region was used for the collective dose estimation, then mortality statistics for the global population should be used, which would result in lower impacts than are calculated here. Pollution impacts would not be affected greatly, as European mortality statistics are generally similar to the UK.

Some of the impacts in the construction materials chain were also calculated using simplifying assumptions. Many metal ores are imported from across the world, and little is produced within the UK. Therefore, a more complete treatment of these impacts would use safety statistics from the relevant country of import, or from a range of countries if necessary. Obtaining such statistics can be difficult, but would be possible in principle. As discussed above, the mortality rates of the exporting country would also need to be used in the analysis. One other impact is that may be given more realism is that of pneumoconiosis from CWP in coal mining activities.

Miners who work deep underground are much more likely to contract CWP than miners who work on opencast mines, due to the problems with ensuring adequate ventilation. The impacts of CWP have been assessed using mortality statistics that are a result of exposures a few decades ago. Therefore, if the trend since then has been towards more opencast mining than deep mining, then the pneumoconiosis impacts will be overestimated. To provide a more accurate calculation, it would be necessary to estimate the number of fatalities caused by CWP resulting from exposures in opencast mines. Such statistics are not available and so a more accurate estimate is not possible.

Other simplifying procedures include assumptions about wind backup and storage. This would be essential for substantial amounts of wind power on the system (typically in excess of 20-25% see Rockingham and Taylor (1981) [171]). Including backup considerations would mean that some of the operational risks associated with wind would be replaced temporarily by operational risks associated with the backup technology, which would probably be gas. On the other hand, additional risks would arise as a result of the construction of the gas plant and operating it in standby mode. Including energy storage for wind, which would likely be pumped storage, would result in increased impacts, as a pumped storage system requires large quantities of material in return for relatively small outputs of energy.

19.3 Implications for Future Generation Scenarios

These results have implications for the composition of the UK electricity generating system in future scenarios. In particular, the results indicate that systems with high levels of fossil and/or wind technology, and low nuclear will present greater risks, both to workers and to members of the public, than a high nuclear, low fossil/wind scenario. Such analysis of scenarios is based on the incremental impacts of each technology. For example, a scenario with an electricity generation mix composed of 50% wind (evenly split between onshore and offshore technologies), 20% gas, 20% coal and 10% nuclear produces impacts that are eight times greater than a scenario with 80% nuclear, 10% wind, 3% gas and 2% coal. Clearly such results are subject to numerous caveats, such as those described in section 13.2. One of the most important caveats is that present situations are assumed to apply to future conditions.

It is highly probable that all technologies studied will tend towards higher levels of safety. Wind technologies represent relatively recent ways to generate electricity, when compared with nuclear and fossil. This is perhaps why wind technologies were found to have relatively high impacts. For most successful technologies, safety considerations usually lag behind growth of the technology. Also, the earliest reductions in risk are usually the largest, with further risk reductions getting increasingly difficult and expensive. So, although wind technologies present greater risks than nuclear, they also have the greatest potential to undergo a larger reduction in such risks.

19.4 Comparisons with Other Studies

There have been four major studies that have considered the health effects of electricity generation by various different technologies including renewable technologies. These are: Inhaber (1982) [112], which was published in the early 80's and analysed American and Canadian technologies; Fritzsche (1989) [86], which was published in the late 80's and analysed power plants that were used in Europe; Ball et al (1994) [15], which was published in the early 90's and analysed UK power systems; and ExternE (1999) [78], which was published in the late 90's and analysed European technologies. The different time periods over which the studies were performed, the different technologies assessed and the differences in the risk metrics quantified means that a direct comparison of the results of these studies is not possible. However, it is possible to compare the results in terms of their rank orderings of the different technologies. This can be done by scaling the results of the analyses against the highest risk and lowest risk found in the study so that all the calculated impacts lie between zero and unity, with the lowest impact taking a value of zero and the highest impact taking a value of unity. The orderings of the four studies can then be compared with the orderings of the present study, without having to transform the results into some common metric, such as an equivalent hazard elimination premium.

One feature that must be necessary for these scaled values is that the quantity that the impacts are normalised against must be the same. A risk per person would not be comparable with a risk per unit energy, even after scaling the results in the manner described. Fortunately, all studies used the same quantity for normalising the impacts, which was the amount of electrical energy generated by each technology, as was used in this report. It is also fortunate that most of the studies classed the impacts in the same manner as was used in the present study, namely in terms of immediate and delayed impacts to workers and to the public, although each study labels these impacts in their own manner. The exception to this is the ExternE study, which categorise the risks slightly differently. It was possible to apportion these results according to the present classifications in a manner that will be described below. Abnormal impacts have not been compared, however, as they have been treated differently in all studies. Only the present study and the study by Ball et al treated onshore and offshore wind risks separately. For the others, it will be assumed that the two present the same risks

To compare the results, three regimes will be looked for. The first will be when there are high impacts, taken as being values in the range 0.5 – 1.0. The second is when there are medium impacts, taken as values that lie in the range 0.1 – 0.5. The third regime is when the impacts are low, which is assumed to be values that lie in the range 0 – 0.1. These limits are arbitrary and taken as a guide to judgement, not as a fixed limit.

The comparison of the immediate occupational impacts is shown in Figure 45. The studies by Ball et al and Fritzsche have the highest values for all generating technologies. This is a reflection of the lesser weight the studies place on pollution impacts more than anything else. This is also true to a lesser extent of the Inhaber study. Both the present study and the ExternE study have low values as a result of higher impacts from pollution emissions. These differences can be seen to be a consequence of recent developments in the health effects of widely circulated pollution emissions. The risks from each technology found by the present and the ExternE studies are classed as low. Inhaber’s results would agree with this for nuclear and gas. All the other impacts found by the other studies are classed as medium. All the studies were found to agree that the wind technologies and coal are ranked as the highest, but there are differences about how nuclear and gas rank against each other. The Fritzsche and Ball et al studies suggest that nuclear should be ranked with the coal and wind technologies, while gas is ranked lower. The Inhaber, ExternE and present studies rank both nuclear and gas as low compared to coal and wind.

The comparison of delayed occupational fatalities is shown in Figure 46.All studies found these risks to be zero or low for the nuclear, gas and wind systems. Coal was also found to be low in the Inhaber, ExternE and present study, but the Fritzsche and Ball et al studies found that coal has a low to medium impact. Again, this reflects the lower weight placed on pollution effects by these studies. These latter studies, the ExternE study and the present study agree on the ranking of risks – that coal is ranked the highest and nuclear is ranked second highest, while gas and wind are ranked last, being either very low or zero. Inhaber slightly disagrees, ranking nuclear the highest and coal as second highest. Wind is ranked third and gas ranked as lowest.

Figure 47 shows the comparison of immediate public fatality risks. The only impact that is greater than the 0.1 assumed threshold is the coal risks in the Fritzsche study. All others are well below this threshold, indicating that all studies agree that these risks are low. None of the studies have rankings that agree with each other. The main reason for this may be because these impacts are generally not given great priority. For example, the ExternE study does not report any such impacts for nuclear and coal. Ball et al also do not report these impacts for nuclear and gas. Therefore trying to compare these impacts is difficult will not be pursued further here.

The risks resulting from delayed public impacts are shown in Figure 48. This graph is shown on a logarithmic scale due to the large variations in the values. It is immediately obvious that all studies agree that the coal public impacts are the greatest risk out of all generating system impacts. These are therefore the only impacts that can be classed as "high". The Fritzsche, Ball et al and ExternE studies found risks for gas that can be classed as low/medium, as they approach or are above the 0.1 threshold. The ExternE study also found medium impacts for nuclear power. All the other impacts were found to be low. In terms of rankings, ExternE and Ball et al agree that the ranking from highest to lowest is coal, gas, nuclear and wind, with the latter impact being zero. Fritzche's ranking is coal, gas, wind and nuclear.

Inhaber finds the ranking to be coal, wind, nuclear and gas. This is slightly different to the present study, which finds the ranking to be coal, wind, gas and nuclear.

Finally, the results from all aggregated impacts are shown in Figure 49. Again, a logarithmic scale is used. Again, all agree that coal poses the greatest risk out of all the technologies assessed. There are differences in the ways the other technologies are ordered. The Fritzche and ExternE study rank gas and nuclear the second and third highest respectively, while wind is ranked the lowest. Ball et al rank offshore wind as the second highest, nuclear the third highest and onshore wind and gas as the lowest. Inhaber ranks the technologies as coal, wind, nuclear and gas, while the present study would rank them as coal, onshore wind, offshore wind, gas and nuclear.

Thus, whilst all studies agree on the high risks produced by pollution emissions of coal plants, there is some disagreement in the rankings of nuclear and wind. Many of the nuclear impacts found in the studies were due to radiation, and expressed in terms of additional fatalities. However, the approach in this study is to use a finer measure of detriment – the loss of life expectancy. In the case of radiation, death often does not occur until after some significant delay. Hence a death due to radiation is weighted less than an immediate death, which may produce the difference in ordering. Another different feature of this study which may explain the discrepancy found for the wind technologies is that a much more complete assessment of the impacts in the construction materials chain has been performed, where the particulate emissions resulting from manufacturing, waste disposal and transportation have been included. This probably explains some of the higher impacts found for wind. The use of more finely grained fatality statistics relevant to each generating technology is also a novel feature of this study, as beforehand, only general fatality rates were available, e.g. average construction fatalities for the whole industry, rather than for specific power plants.

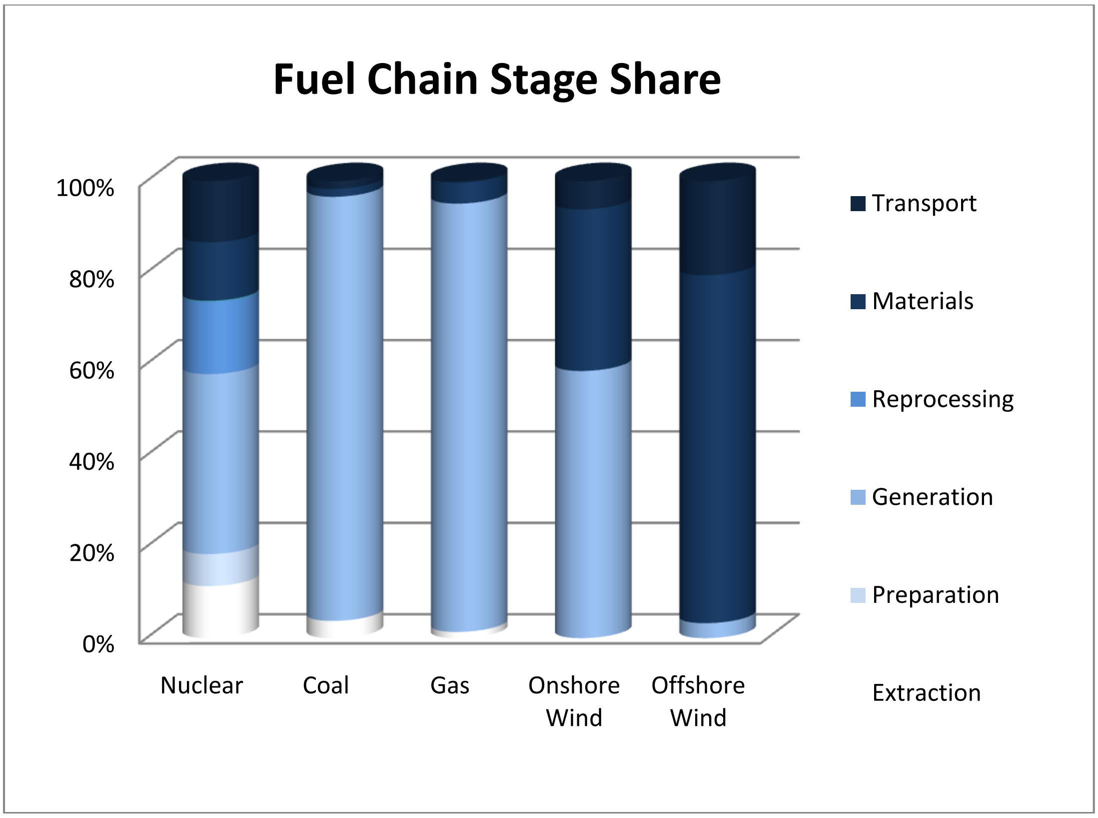

Figure 41 Proportion of total impacts at each fuel chain stage for each technology.

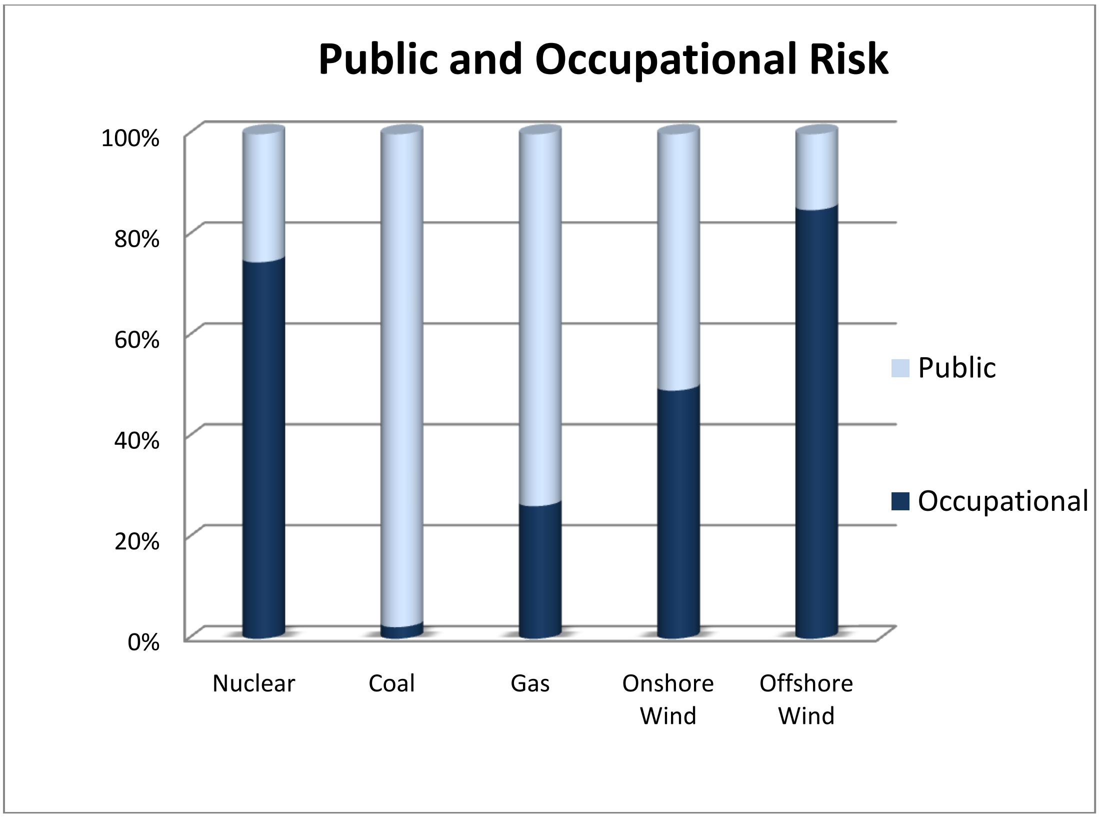

Figure 42 Public and occupational risk proportions of total impacts.

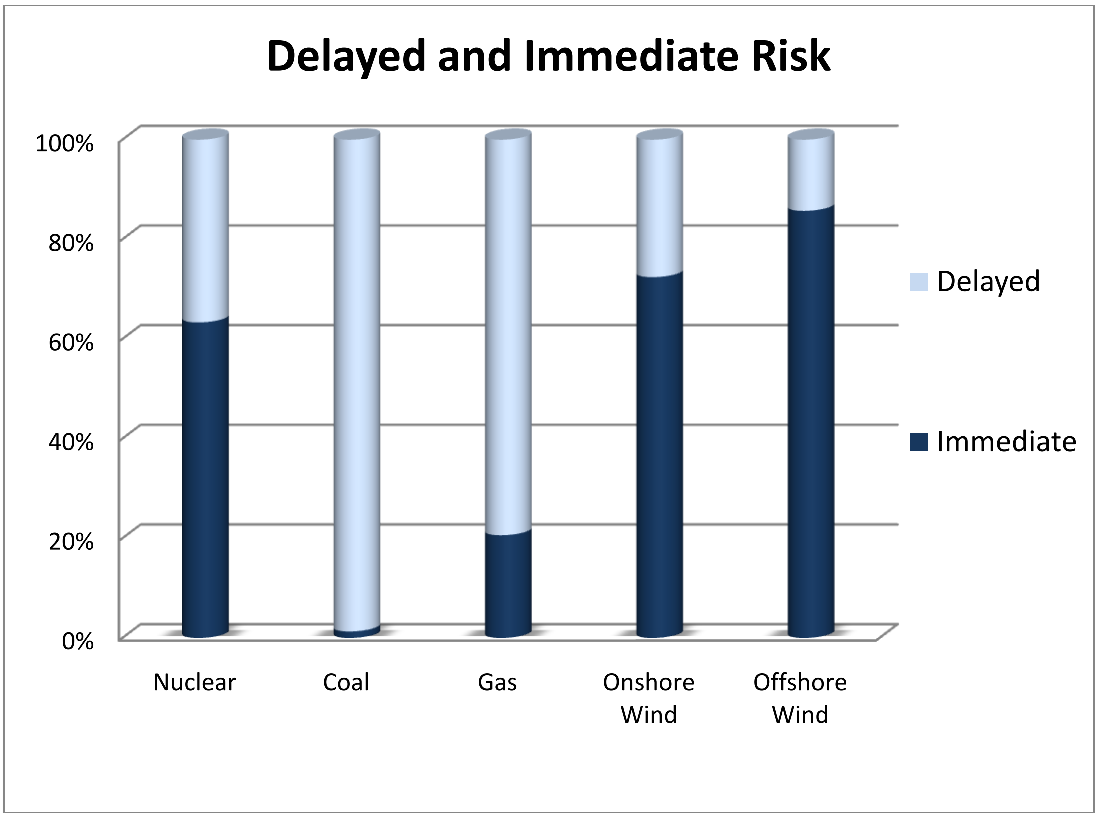

Figure 43 Immediate and delayed risk proportions of total impacts.

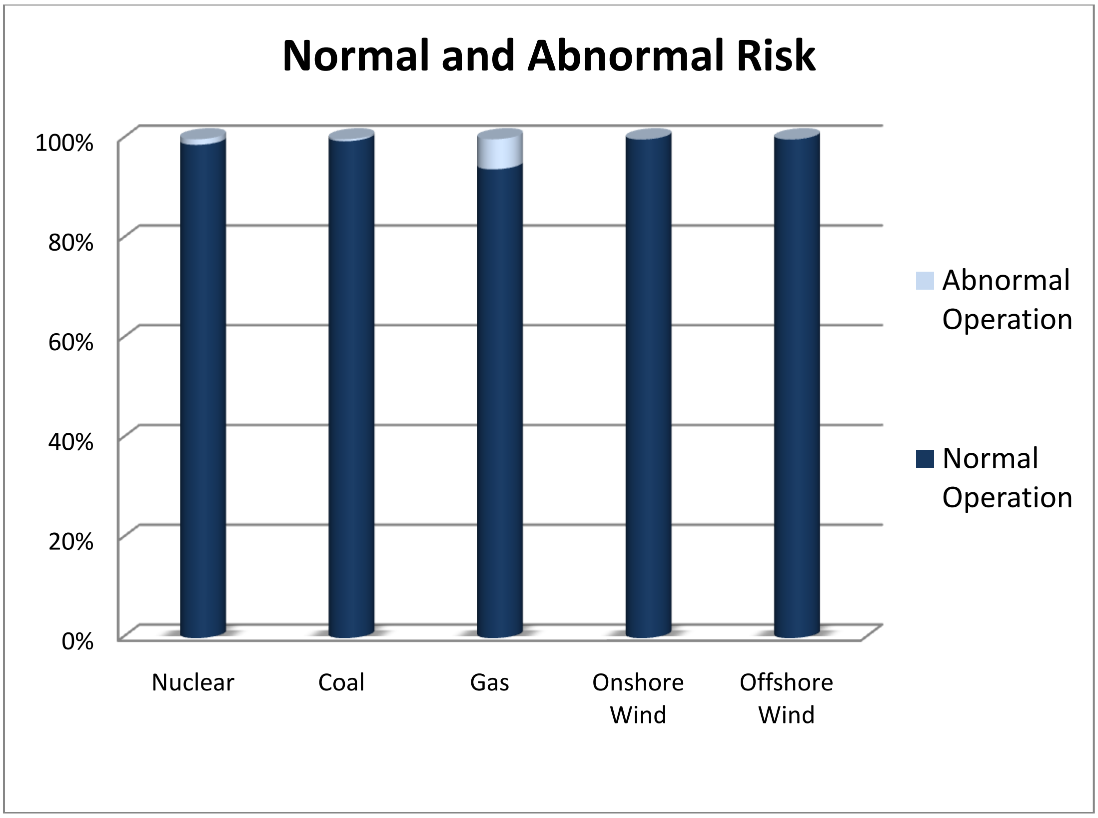

Figure 44 Normal and abnormal operation risk proportions of total impacts.

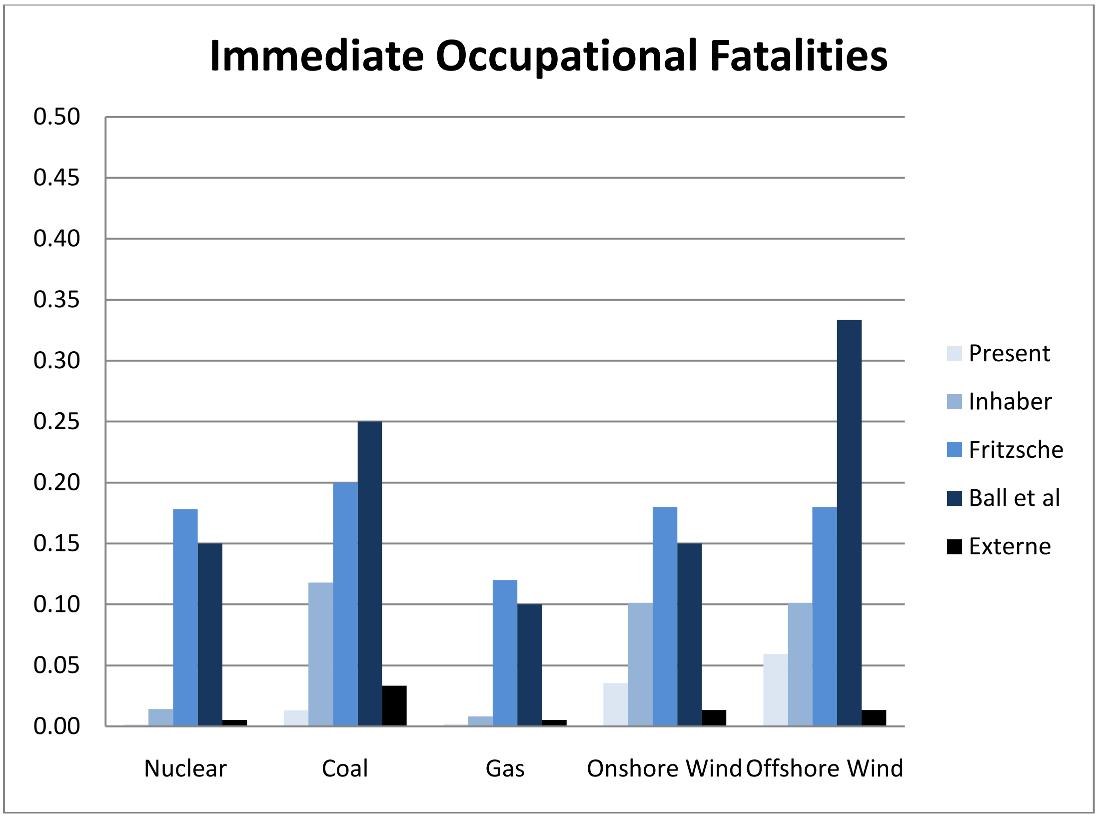

Figure 45 Comparison of immediate occupational fatality risks.

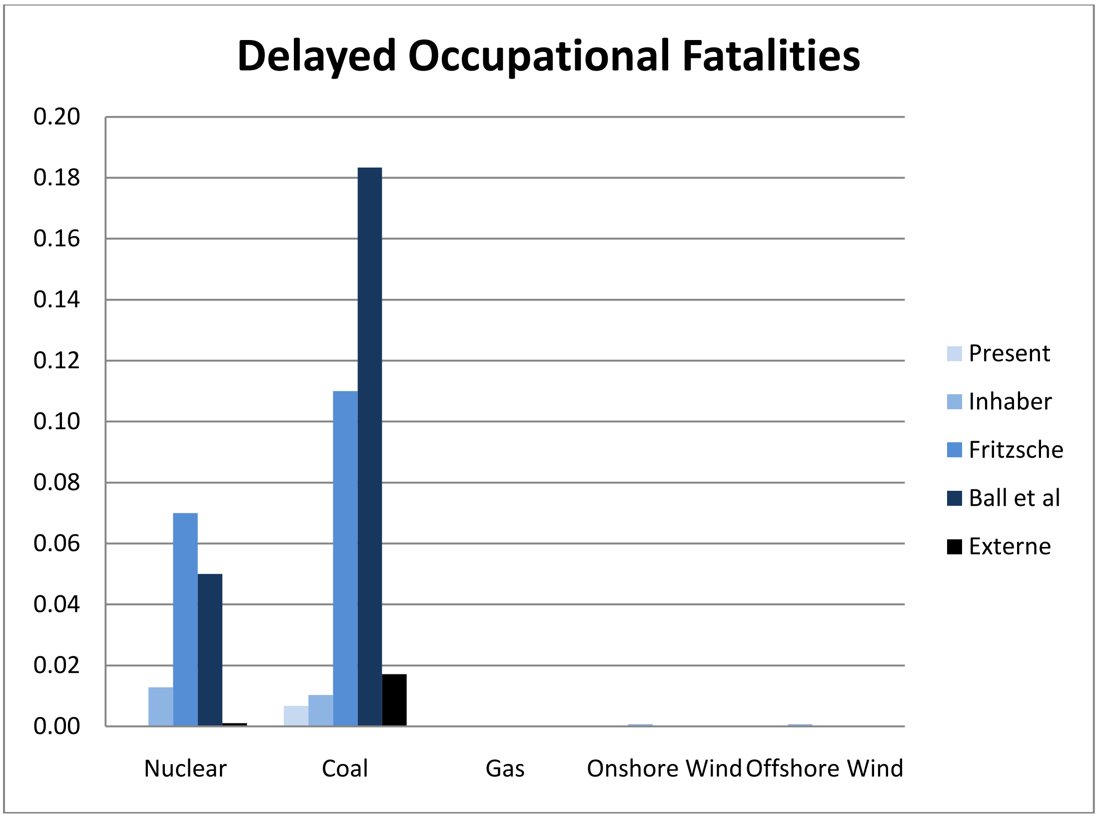

Figure 46 Comparison of delayed occupational fatality risks.

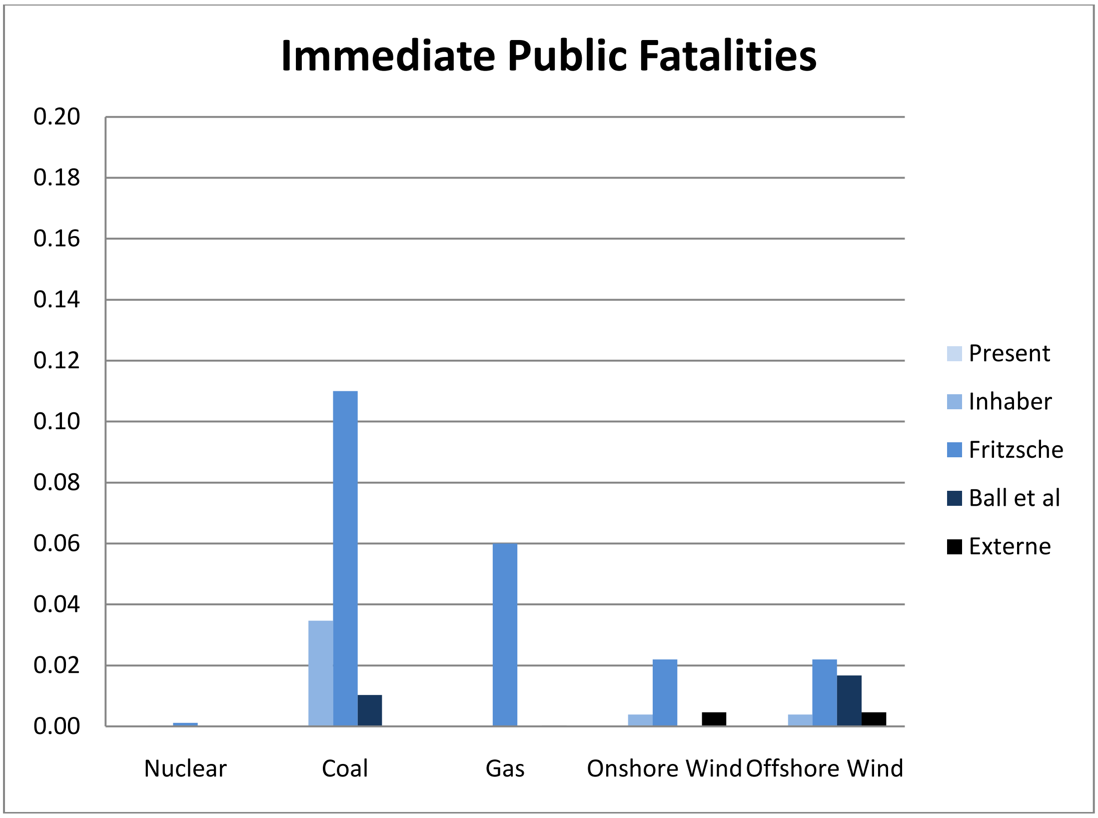

Figure 47 Comparison of immediate public fatality risks.

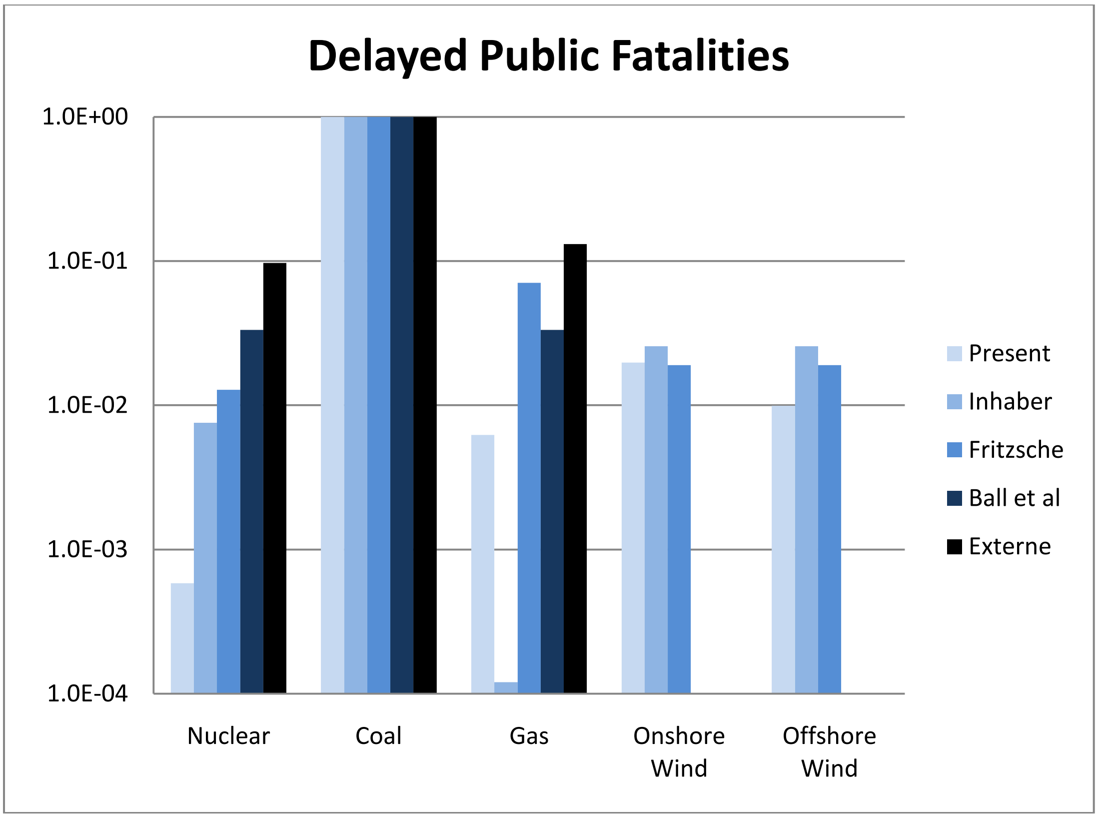

Figure 48 Comparison of delayed public fatality risks. Note the logarithmic scale.

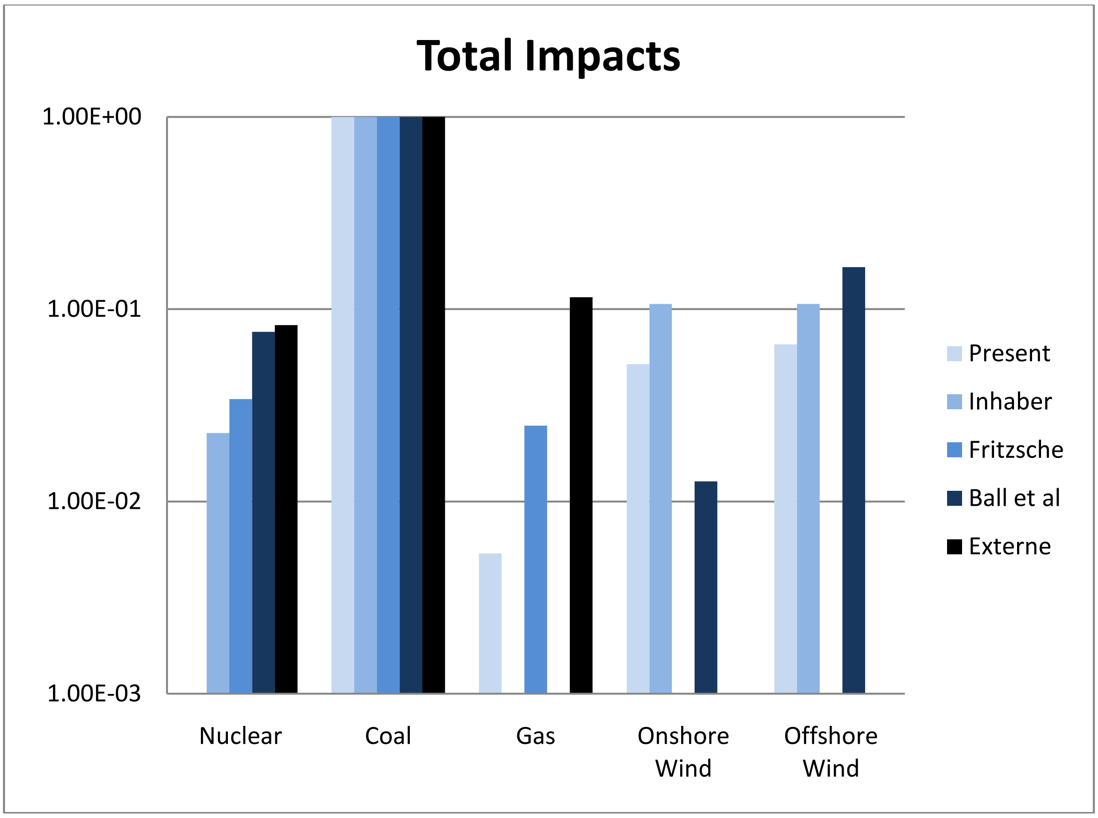

Figure 49 Comparison of total risk. Note the logarithmic scale.

Part 3 Conclusions and Further Work

Chapter 20 Conclusions

20.1 Conclusions Regarding the J-Value Framework

The J-value framework was described in part one of this thesis. In chapter three, the foundations of the framework were described. It was shown how the life quality index, which is of the form of a discounted lifetime utility function, may be used as an indicator of individual well being. By analysing the trade-offs made at an individual and a societal level between free time, life expectancy and income, an upper bound for safety expenditure can be derived. The J-value is then the ratio of actual expenditure to the theoretical maximum.

Chapter four gave an overview of the methods used for calculating life expectancy. These were developed further in chapter five, where it was shown how perturbations in the underlying hazard rate change the life expectancy. Two general risk models were introduced in this chapter – an absolute risk model and a relative risk model. Some general results were proved in the case of limiting exposures and responses, and specific examples of exposures to radiation and pollution were also discussed. This development extended the existing framework, which had heretofore been primarily concerned with radiation exposures, which follow an absolute risk model.

Chapter six described the method for calculating the work-life parameters, while chapter seven derived common metrics used in health and safety valuations – the value of temporarily preventing a fatality, and the value of a life-year. The HEP was also introduced as a useful metric for risk comparison.

Chapter eight described in detail how to estimate the parameters in the J-value equation, and how to assign tolerances to them. It was shown how most of the J-value input parameters could be estimated with good accuracy.

In chapter nine, a sensitivity analysis was performed in which the sensitivity coefficients of the J-value were calculated. It was shown that, whilst the J-value is relatively robust, it is most sensitive to uncertainty in the change in life expectancy parameter. The sensitivity analysis also considered the effect of the use of simplifying assumptions in some stages of the J-value derivation. Again, it was found that the J-value was insensitive to the use of more accurate data. As the assumptions simplified the calculations considerably, this provided justification for their use.

In chapter ten, the J-value was extended to include valuation of financial risks. It was shown that corresponding J_2 and J_T values could be derived. The numerical method used in the calculations for some of the parameters was also described. Part one then concluded with some example calculations in chapter eleven.

20.2 Conclusions Regarding the Comparative Risk Analysis

The health risks from the generation of electricity by nuclear, coal, natural gas, onshore wind and offshore wind technologies have been assessed using the J-value methodology described in part 1. This was the first time the J-value has been used in any comparative risk assessment of energy systems. The J-value uses the loss of life expectancy as a main indicator of detriment. The impact is then monetised to give the "hazards elimination premium" (HEP). This is the maximum reasonable amount to spend on eliminating the risk. Risks were delineated according to whether they were to workers or to the public, and whether they were immediate or delayed risks.

Immediate risks are those in which death occurs at or shortly after the time of exposure. Delayed risks are those in which death occurs after some substantial delay. Sources of delayed risks are exposures to radiation, mineral dust, and particulate matter. The risks of major accidents are also classed separately as an abnormal impact. Such abnormal impacts can occur from large nuclear accidents, coal mine accidents and gas or oil explosions for offshore accidents. The environmental impacts of these abnormal accidents were also quantified in terms of a financial HEP, although it was found that these impacts are generally much smaller than the health risks and so can be neglected.

A complete fuel chain approach was taken, incorporating all impacts at each stage of the chain. These stages include extraction, preparation, generation, reprocessing and waste storage and disposal. Also included was a complete construction materials chain. Construction materials also require that raw materials are extracted before being shipped to a manufacturing facility. The materials are then shipped to the power plant or other relevant fuel chain facility for construction. After decommissioning, the materials are then recycled or disposed of. All of these stages also have impacts which have been accounted for as far as was possible. Impacts were also assessed for current and incremental impacts. Current impacts are the present value of all impacts resulting from currently operational facilities over the assessed time period of 2010 to 2070. Incremental impacts are the additional impacts arising from new facilities. All impacts are normalised against the amount of electrical energy generated by each technology. Incremental risks are arguably the more important metrics for risk comparison, as they offer information on the effects of future planning choices over the method of generating electricity that would be more useful to a decision maker. The incremental impacts have therefore been the main focus of the analysis.

In terms of incremental impacts, it was found that for immediate occupational impacts, the highest risks are from coal and the wind technologies. For immediate public impacts, perhaps surprisingly, the analysis indicates that wind has impacts comparable to- or larger than- the other technologies, reflecting the large quantities of materials required to generate electricity from such a diffuse source. Coal power generation presents the only occupational delayed impact that is above the

£0.5M/GWa significance threshold, although these estimates have large uncertainties. Delayed impacts to the public are larger, with risks being smaller from nuclear unless the effects of radiation are treated very conservatively by summing effects over the world population over very long time periods in which case these risks from nuclear power production would increase by about an order of magnitude, making them comparable to gas and wind. However, treating the effects of radiation in this way involves amplification of vanishingly small risks, and is usually not useful to the decision making process.

Impacts arising from abnormal operation from all the technologies are relatively small apart from coal, where the impact is somewhat higher. These latter estimates depend upon the source of the coal. Using current and historical data on normal and abnormal mining accidents in some supplying countries would substantially increase these risks.

Aggregation of impacts provides a single, if approximate, indicator of total detriment, which is appropriate provided due acknowledgement is made of the types of hazards which make up the indicator. In terms of total detriment, using the assumptions outlined above and in the tables, it is indicated that nuclear power presents the lowest risk.

Nuclear power is followed by gas, onshore wind and offshore wind, which have indicative impacts that are approximately one order of magnitude greater, although there is considerable uncertainty attached to the onshore and offshore wind impacts. The analysis suggests that coal impacts are relatively high, being a few orders of magnitude greater than the nuclear impacts. Although actual numbers must be treated with caution given the assumptions required, sensitivity analysis described in chapter 19 suggests that the general conclusions are likely to be robust.

A comparison of the incremental and current risks shows that nuclear, coal and gas have incremental risks that are lower than their current risks. This indicates "risk efficiency", meaning that the impacts of new build are less on a per GWa basis than the existing plants. For example, this can be because of reduced pollution or radionuclide emissions. Onshore wind has incremental impacts that are broadly similar to current impacts, meaning that new plants produce the same amount of risk as the current plants. Offshore wind has incremental impacts greater than its current impacts, indicating that new facilities are "risk inefficient", producing more risk per unit electricity than current facilities. However, wind power is the most recent of all the assessed technologies, and is therefore more likely to achieve greater reductions in risk as it becomes more mature.

20.3 Overall Conclusions

The aims of this research, as laid out in chapter one, are to:

1. Validate the J-value framework as a suitable and robust tool for risk assessment and analysis.
2. Compare, in a consistent manner, the risks posed by various electricity generating systems in the UK using the J-value framework.

It was intended that these aims would be achieved through the following objectives:

1. Extending the existing framework by incorporating more general risk models in the loss of life expectancy calculations, and conducting uncertainty and sensitivity analyses.
2. Use the J-value framework to develop a common metric that can be used to compare the risks from electricity generating systems on a consistent basis, i.e. in such a manner that does not bias the results towards any particular electricity generating system.
3. Develop a framework for the comparative risk analysis that will incorporate all relevant risks involved in the generation of electricity for each system in a manner that will ensure a fair and valid comparison.

In part one the existing J-value framework was extended in chapter five through the development of more general risk models. Uncertainty and sensitivity analyses were also conducted in chapters eight and nine respectively, and found that the J-value could be quantified with accurately and was robust against the inherent uncertainties in the input parameters, and also against the use of simplifying assumptions. Thus objective number one has been completed, and the first aim has been achieved.

In chapter six, the “hazard elimination premium” was introduced as a suitable common metric for risk comparisons that had been derived from the J-value framework. This was then used in the comparative risk analysis of electricity generating systems. The framework for the risk comparison was presented in chapter 13, where the issues surrounding how to ensure a fair and valid comparison of the different generating systems was discussed. Chapters 14 to 19 then described the comparative risk analysis and presented the results. Thus the second and third objectives have been met and the second aim of the thesis has been achieved.

This thesis demonstrates the strength of the J-value framework in using loss of life expectancy as an indicator of harm, which is particularly relevant for delayed risks from radiation and pollution. The J-value method thus allows different sources of risk to be compared directly and also provides a technique for monetising risks that is objective and more robust than currently used questionnaire-based methods used to imply a “Value of Preventing a Fatality”.

This thesis is not intended to provide the final word on the relative safety of different electricity technologies. Risk quantification can account only for measurable risks, and there may be important factors that are difficult or perhaps impossible to measure at our current level of understanding, such as reputation and trust. As has been mentioned, risk estimates need to be examined carefully and the limitations and uncertainties of the results should be recognised. However, the thesis is intended to complement the existing literature using a new approach and to further the debate on an issue that is becoming increasingly important in a world unsure of how its energy needs are going to be met.

It is also hoped that this study has demonstrated how an improved understanding of the relative merits and costs of different technologies can be promoted through objective analysis, as can be accomplished by the J-value.

Chapter 21 Further Work

21.1 Further Work Regarding the J-Value

Many of the concepts underpinning the J-value are well developed and do not need extending in any way. The most recent development of the J-value method was the assessment of tolerances, both of the input parameters to the J-value, and of the J-value itself. These assessments were presented in chapter 8, where it was noted that, although the standard deviation of the J-value can be determined, it is not yet possible to calculate the tolerance limits, as the distribution of the J-value is not known. This is because the J-value is the product of a number of parameters, many of which were found to be normally distributed, although the GDP per person, *G*, was found to have the ratio distribution. Furthermore, the random variables have different means and standard deviations. Although it is known that the product of a large number of independent normal random variables will have a log-normal distribution (through application of the central limit theorem), this will likely be a poor approximation to the J-value distribution, as only a few random variables are involved, not all of which are normal (or independent, if the discount factor is used). It would be possible to infer the distribution of the J-value though simulation of the random variables. This would then allow the tolerance limits at a specified level to be determined. This would be the main area of further research for the J-value.

Another recent addition has been the assessment of pollution exposures on the change in life expectancy. The response of these exposures was assumed to be a step function that began at the time of exposure and ended 15 years later. However, as was noted in section 5.9, the actual response function is more likely to be an exponential decline which falls away faster than the step function would indicate, but would also last for longer than 15 years. Producing a more accurate response function may also be another topic of research.

21.2 Further Work Regarding the J_2 and J_T-Values

The J_2 and J_T-value, and the associated work on the limits of the risk aversion, are more recent developments and consequently, there is a wider scope for further research. Although not presented in this thesis, work has been carried out on calculating the average permission point, $\varepsilon_{pp.ave}$, taken by an individual wishing to insure against all types of risk that he or she may face, see Thomas et al (2010b) [191], and Waddington et al (201x) [199]. This was found to lie in the range 0.8 – 1.0 following sensitivity analysis of a wide range of parameters appropriate to an individual or small organisation. These include assets, A, discrimination limit, δ_{dis}, and the maximum cost of the risk. It was also found that for large organisations, a suitable average risk aversion was 0.1, reproducing the view that large organisations will be risk neutral unless faced with a risk that poses a threat to their viability. These results may be extended into specific cases of risk. This would entail overlaying a probability distribution for the associated consequences of the risk. This could be done by setting $p_1 = p_1(c)$, which would reduce the number of independent variables by one. For example, one may wish to assess the risks from earthquakes or storms, or some other natural hazards. For such hazards, an inverse power law distribution may be appropriate to use. Instead of averaging over all probabilities and consequences, it would be possible to select the correct figures from the probability distribution. This would then enable calculation of the average and maximum permission points, which would then enable the maximum reasonable spend to be determined.

It has also been found that, for risks that have a small expected loss (e.g. < 1% of initial assets), the permission point may have negative solutions, corresponding to "risk seeking" behaviour. These results were discounted from the original research, as it was assumed that decision makers would usually be risk averse. Nevertheless, it may be of interest to find the level of risk at which decisions transition from risk averse to risk seeking. The implication of this behaviour is that it would be possible to justify spending less than the expected loss, so that $m_{r\ max} < 1$.

In addition to these issues, an assessment of the tolerances of the J_2 and J_T values would also be an aspect for further research that would be useful.

21.3 Further Work Regarding the Comparative Risk Analysis

In any such complex analysis, there are always numerous additional topics for further research. These topics can be divided into two areas. These are: broadening the scope of the analysis, and improving the accuracy and robustness of the current results. In the latter category, some mention has already been made of the ways in which improvements can be made. These include using mortality statistics specific to the region in which the exposure to risk occurs to calculate the loss of life expectancy. These would be relevant to uranium mining practices, European exposures to pollution, collective radiation exposures over Europe and the world, and extraction of ores that are imported into the UK. Fatality rates in the countries which the ore is extracted would also help to improve the accuracy of some of the construction materials impacts. This is because currently, quarrying statistics are used as a proxy indicator for the effects of metal ores, which are not mined in great quantities in the UK. If such ores were imported from a range of countries, then a suitable range of risk estimates would be required.

It has also been noted that the estimates of the pneumoconiosis risk may be overestimated, if the trend for mining is towards more opencast mining than deep underground mining. If it were possible to determine the type of mine worked on by each sufferer of CWP then a more accurate pneumoconiosis impact could be obtained. The method for estimating this impact itself may produce overestimates. This method is described in Appendix C. Better estimates would require more information on the exposures experienced and the likely response. Also discussed were ways in which the assumed response to pollution exposures could be improved. This ways of doing this has already been discussed in section 21.1.

Other methods of quantifying uncertainty may also help improve the robustness of the analysis. Currently, immediate occupational statistics are calculated using Poisson statistics to determine the 95% confidence intervals of the exposure rates when there have been few fatalities. For nuclear and wind technologies there were low observed counts, and this resulted in some wide confidence intervals, and hence large uncertainty in the estimates of the impact. While uncertainty is a part of scientific research and does not mean that the study is flawed, it was found to strongly affect these technologies in comparison to coal and gas, where there have been many more fatalities, but also more electricity produced. An alternative method of quantifying the uncertainty to be attached to the immediate occupational risks would be desirable, if only to validate the existing finding of a wide confidence interval.

There are also many areas into which the analysis could extend. It has already been mentioned that coal plants emit large amount of toxic chemicals that are known carcinogens. These become widely circulated and expose many people to low levels of these substances. There is currently not enough adequate information available in order to quantify the mortality effect of exposures to these substances. However, they may be substantial.

Another important issue that has been highlighted recently is the effects of Chinese rare earth mining, in which neodymium is extracted. One use of neodymium is in permanent magnets in wind turbines. Rare earth mining has been associated with serious environmental damage and health effects resulting from exposures to toxins as well as a poor mining record. This effect has not been quantified here as neodymium was not found to be used in sufficient quantities to warrant assessment. However, it may be possible to incorporate such an assessment, which would be a useful feature as this impact has received much attention recently.

The analysis of wind turbine impacts could also be extended to include back-up and energy storage considerations. If wind power is to achieve considerable electricity penetration in the UK, then issues of this sort must be addressed. Were wind speeds to drop for a considerable length of time, then it would be necessary to provide electricity from an alternate source. Currently the best option is to use gas turbines, which can be dispatched easily. It would then be necessary to include the impacts from constructing and operating the turbine, as well as extracting the gas and other stages in the fuel chain. This could be done by either summing the impacts for wind and gas together or performing a weighted average. However, there may be a complicating factor in that the gas plants would not be providing continuous baseload electricity, but would be operated in standby mode. This could be modelled by reducing the capacity factor of the gas plant. There may be other effects of standby operation which would need accounting for, such as the working practices in a station operating in standby mode being different to a baseload plant, so that the occupational risk profile may be different.

Another feature necessary to address is energy storage. Storage is necessary for large wind systems so that any quantities of energy produced during times of low demand can be stored for use when demand is higher, thus producing greater efficiency, and reducing the need for reliance on back-up. The main current storage technology is pumped hydroelectric storage, whereby water is held in an elevated dam thereby containing stored gravitational potential energy. Including impacts from such a source would likely substantially increase the impacts as these systems require large quantities of material and consume the energy produced by wind technology, thereby reducing its effective capacity factor. There are other methods of storing energy, such as in flywheels or fuel cells, but none have yet been implemented on a large scale and so estimating their impact would be difficult.

There are other hazards that have not been quantified but may become increasingly important. The HSE has recently launched an emerging energy technologies programme to investigate some of the risks involved with new power production methods, see HSE (2010) [103]. One important identified hazard is that resulting from the use of carbon capture and storage systems (CCS). Such systems involve capturing carbon dioxide at the point of production, compressing it to high pressures, transporting it through underground pipelines, and depositing it into underground geological structures where it can be stored securely. CCS systems require carbon dioxide to be handled in large concentrations and volumes. As carbon dioxide is a toxic asphyxiant, this may present some large hazards. Another hazard lies in the transportation of highly pressurised carbon dioxide through underground pipelines, where there is a risk of a major pipeline rupture near to population centres.

Other hazards identified by the HSE are those involved with new coal technologies. Coal generation may in the future involve extraction of methane from coal deposits, gasification of the coal, use of high temperature supercritical plants, or co-firing of coal with biomass. Each of these technologies carries the risk of major gas explosions or catastrophic failures of the boilers or pressure vessels.

There are also risks of a major accident involved with wind turbines that may require further quantification. These include the risk of a turbine collapse, blade throw or serious ship/turbine collision for offshore wind power. Although most collisions of this type would not be serious, the possibility cannot be ruled out that a major accident involving a passenger ferry or an oil tanker could result in large loss of life or environmental damage.

Other ways in which the analysis could be extended would be to include other technologies. In addition to future developments of wind technology involving ever larger turbines that can generate electricity, there are other forms of electricity generation that are becoming ever important. These involve biomass, solar photovoltaic, and energy from waste schemes, to name a few. Although safety statistics for many of these technologies are currently sparse, it would be possible to perform an initial analysis based on material requirements, which may constitute a large part of the total risk.

Finally, another area in which the analysis could extend into would be to include more environmental damage costs, which could be assessed using the J_T framework. The environmental damages associated with large accidents studied in this analysis were found to be small compared with the other health risks. Other more routine environmental impacts may have a more significant role. In particular, assessing the damage from emissions of carbon dioxide may be particularly relevant to current the energy debate. Such an analysis would be based on the risk to operators of being financially penalised for such emissions. This could also be done for other substances such as sulphur dioxide and nitrous oxides.

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Appendices

Appendix A. Proof that the Maximum Reasonable Spend on Human Protection is Invariant under Affine Transformations of the Utility Function

As was discussed in section 3.4, the life quality index (LQI) can be generalised to account for other types of utility function, $U(G)$. The generalised LQI is given by modifying equation (3.5) to:

$$Q = U(G) fX \tag{A.1}$$

The usual form of the utility function is the power function, which will be denoted as $U_p(G)$, and is given as:

$$U_p(G) = G^q \qquad 0 \le q \le 1 \tag{A.2}$$

As has been discussed, q is constrained so as to retain the well established law of diminishing marginal utility. The lower bound can be removed by using the Atkinson utility function, $U_A(G)$:

$$\begin{aligned} U_A(G) &= \frac{G^q - 1}{q} \qquad & q \le 1,\ q \ne 0 \\ &= \ln G & q = 0 \end{aligned} \tag{A.3}$$

In geometric terms, the Atkinson utility function is a scaled and translated transformation of the power utility function. A transformation that scales and translates is known as an "affine transformation". A further utility function, $U_{aff}(G)$ can be introduced which captures these features of the affine transformation, and has both the power and Atkinson utility function as special cases:

$$U_{aff}(G) = \frac{G^q - k_1}{k_2} \qquad q \le 1 \tag{A.4}$$

Where k_1 is a constant which parameterises the translational aspect, and k_2 is a constant which parameterises the scaling aspect of the affine transformation. The power utility function has $k_1 = 0$ and $k_2 = 1$, whilst the Atkinson utility function has $k_1 = 1$ and $k_2 = q$. Different LQIs may be used with these utility functions, and these will be denoted Q_p, Q_A and Q_{aff} respectively.

In order to derive the maximum spend which is then used in the J-value, it is necessary to apply the two trade-offs introduced in sections 3.2 and 3.3. These trade-offs are achieved by imposing two conditions on the LQI, namely:

$$\delta Q(G, X_d) = \frac{\partial Q}{\partial G}\delta G + \frac{\partial Q}{\partial X}\delta X \geq 0 \tag{A.5}$$

and:

$$\left.\frac{dQ}{dw}\right|_{w=w_0} = 0 \tag{A.6}$$

The first condition gives the bounds for the acceptable amount to spend on a scheme, δG, that improves life expectancy, whilst the second condition allows an expression for the parameter, q, which is the only unknown, to be derived.

In order to prove the invariance of the maximum spend to affine transformations, it is necessary to show that the required spend, δG_p from a power utility function is the same as the required spend, δG_{aff} from the affine transformation. The quantities w, X, and δX are all independent of the utility function used, and so will be the same in both cases. The quantity G is the independent variable in the utility functions, so will also be the same. Since q is set by the solution of condition 2, it will depend on the type of utility function used. The value of q arising from a power utility function will be denoted q_p, whilst the q from a general affine utility function will be denoted q_{aff}.

The results using the power utility function have already been derived. The elasticity q_p, is given as:

$$q_p = \frac{1}{\theta}\frac{w_0}{1-w_0} \quad \text{(A.7)}$$

whilst the maximum spend, $-\delta G_p$, is:

$$-\delta G_p = \frac{G}{q_p}\frac{\delta X_d}{X_d} \quad \text{(A.8)}$$

For the general affine utility function, the LQI is:

$$Q_{aff}(G, X_d) = \left(\frac{G^{q_{aff}} - k_1}{k_2}\right)(1-w)X_d \quad \text{(A.9)}$$

Applying the first condition gives:

$$\delta Q_{aff}(G, X_d) = \frac{q_{aff} G^{q_{aff}-1}(1-w)\delta G_{aff}}{k_2} + \left(\frac{G^{q_{aff}} - k_1}{k_2}\right)(1-w)\delta X_d \geq 0 \quad \text{(A.10)}$$

Re-arranging gives the maximum spend, $-\delta G_{aff}$, as:

$$-\delta G_{aff} = \frac{G}{q_{aff}}\frac{\delta X_d}{X_d}\left(\frac{G^{q_{aff}} - k_1}{G^{q_{aff}}}\right) \quad \text{(A.11)}$$

Applying equation (A.6), to (A.9), with the usual $G(w) = Aw^{\theta}$ substituted in, gives:

$$\begin{aligned} \left.\frac{dQ_{aff}}{dw}\right|_{w=w_0} &= \frac{d}{dw}\left[\left(\frac{A^{q_{aff}} w^{q_{aff}\theta} - k_1}{k_2}\right)(1-w)X_d\right] \\ &= \frac{X_d}{k_2}\frac{d}{dw}\left[A^{q_{aff}} w^{q_{aff}\theta} - A^{q_{aff}} w^{q_{aff}\theta+1} + wk_1 - k_1\right] \\ &= 0 \end{aligned} \quad \text{(A.12)}$$

Performing the differentiation gives:

$$q_{aff}\theta A^{q_{aff}} w_0^{q_{aff}\theta-1} - \left(q_{aff}\theta+1\right)A^{q_{aff}} w_0^{q_{aff}\theta} + k_1$$
$$= \frac{q_{aff}\theta}{w_0} G^{q_{aff}} - \left(q_{aff}\theta+1\right)G^{q_{aff}} + k_1 = 0 \qquad (A.13)$$

where:

$$G = G(w_0) = Aw_0^{\theta} \qquad (A.14)$$

is the income at the optimal value of work-time fraction. Since, on average, society selects the optimal value, then G is equal to the average income of an individual, which is simply the GDP per person. The differentiation can be simplified further:

$$\frac{q_{aff}\theta}{w_0} G^{q_{aff}} - \left(q_{aff}\theta+1\right)G^{q_{aff}} + k_1$$
$$= G^{q_{aff}}\left[q_{aff}\theta\left(\frac{1-w_0}{w_0}\right)-1\right] + k_1 \qquad (A.15)$$
$$= G^{q_{aff}}\left[\frac{q_{aff}}{q_p}-1\right] + k_1 = 0$$

Re-arranging for q_{aff}/q_{p}:

$$\frac{q_{aff}}{q_p} = 1 - k_1 G^{-q_{aff}} = \frac{G^{q_{aff}} - k_1}{G^{q_{aff}}} \qquad (A.16)$$

Equation (A.16) cannot be solved analytically for q_{aff}, however, it is clear that when it is substituted into (A.11), all terms involving q_{aff} disappear. Hence after the substitution, equation (A.11) becomes:

$$-\delta G_{aff} = \frac{G}{q_p}\frac{\delta X_d}{X_d} \qquad (A.17)$$

Clearly (A.17) is identical with (A.8), so that:

$$\delta G_p = \delta G_{aff} \tag{A.18}$$

Thus, the maximum reasonable spend is invariant under affine transformations of the utility function.

It is also instructive to investigate the relationship between the two elasticity parameters, as given by equation (A.16), in particular, the case when k_1 = 1, which corresponds to the Atkinson utility function:

$$\frac{q_A}{q_p} = 1 - G^{-q_A} = \frac{G^{q_A} - 1}{G^{q_A}} \tag{A.19}$$

where q_A denotes the elasticity of the Atkinson utility function. This can be rearranged to solve for the power elasticity:

$$q_p = \frac{q_A}{1 - G^{-q_A}} \tag{A.20}$$

It should be noted that the equation is not true at the point $q_A = 0$. The value of q_p at this point can be determined by the usual differentiation as shown above, expect with $U(G) = \ln G$. This gives:

$$q_p = \frac{1}{\ln G} \qquad \text{for } q_A = 0 \tag{A.21}$$

The above equations can be expressed in terms of the respective risk aversions:

$$\begin{aligned} \varepsilon_p &= \frac{\varepsilon_A - G^{\varepsilon_A - 1}}{1 - G^{\varepsilon_A - 1}} \qquad \varepsilon \geq 0,\ \varepsilon \neq 1 \\ &= 1 - \frac{1}{\ln G} \qquad \varepsilon = 1 \end{aligned} \tag{A.22}$$

Thus, the risk Atkinson and power utility risk aversions can be determined from each other, although there is no analytical solution in terms of the Atkinson risk aversion.

However for low risk aversions, the term G^{ε_A-1} becomes much less than unity, so that $\varepsilon_p \approx \varepsilon_A$ for low ε_A. As ε_A gets large, ε_p asymptotically approaches unity. The value of ε_A for given ε_p can be determined numerically. For ε_p = 0.825, ε_A = 0.875. The relationship between ε_p and ε_A is shown graphically in Figure 50.

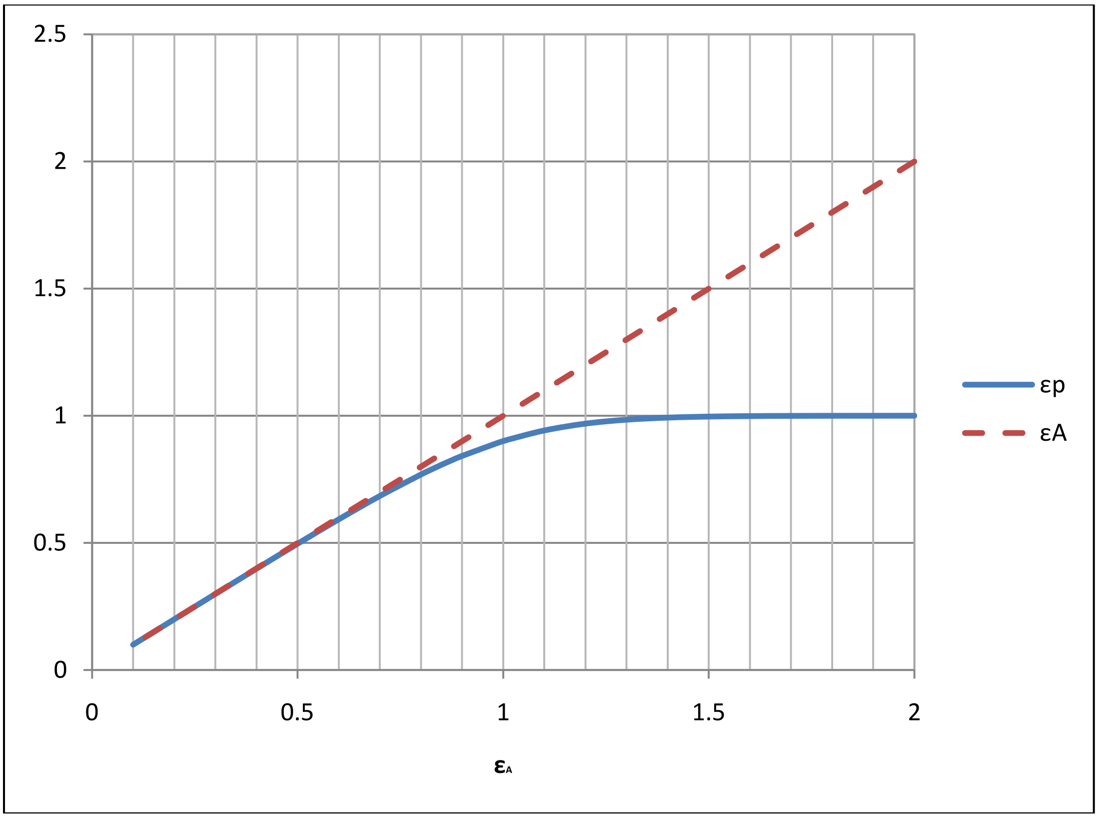

Figure 50 Relationship between power utility risk aversion, ε_p, and the Atkinson risk aversion, ε_A.

Appendix B. Proof that the Moments of the Life to Come are Equal to the Moments of the Life Already Lived in a Steady State Population

The random life to come is a function of age, and is given by equation (4.18), repeated below:

$$\chi(a) = T - a \qquad (4.18)$$

where T is the random age of death. The average life expectancy is the random life to come averaged over all ages of death (i.e. the probability that $T = t$), which has a probability distribution of $f_d(t)/S(a)$, and over all current ages, with a probability distribution a:

$$X = \int_0^\infty p(a) \int_a^\infty (t-a) \frac{f_d(t)}{S(a)} dtda \qquad (B.1)$$

This is then the first moment of the random life to come. The i^{th} moment is:

$$\int_0^\infty p(a) \int_a^\infty (t-a)^i \frac{f_d(t)}{S(a)} dtda \qquad (B.2)$$

It has already been shown that $X = t_{av}$, the mean age in the steady state population, and that:

$$\underset{a}{E}\left[E\left[\chi^2(a)\right]\right] = \int_0^\infty p(a) \int_a^\infty (t-a)^2 \frac{f_d(t)}{S(a)} dtda = t_{av}^2 \qquad (B.3)$$

where t^2_{av} is the mean-square age in the population. Thus, the first and second moments of the random life to come (averaging over times of death and current ages) are equal to the respective moments of the age distribution, i.e. live already lived. It will now be proved that this can be generalised to all higher moments, so that:

$$\int_0^\infty p(a) \int_a^\infty (t-a)^i \frac{f_d(t)}{S(a)} dtda = \int_0^\infty p(a) a^i da \qquad (B.4)$$

First, it is noted that:

$$\int_0^\infty p(a)\int_a^\infty (t-a)^i \frac{f_d(t)}{S(a)}dtda = \int_0^\infty \frac{S(a)}{X(0)}\int_a^\infty (t-a)^i \frac{f_d(t)}{S(a)}dtda$$
$$= \frac{1}{X(0)}\int_0^\infty\int_a^\infty (t-a)^i f_d(t)dtda \qquad \text{(B.5)}$$

and, using the binomial theorem:

$$(t-a)^i = \binom{i}{0}t^i a^0 - \binom{i-1}{1}t^{i-1}a^1 + \ldots + (-1)^i\binom{i}{i}t^0 a^i \qquad \text{(B.6)}$$

which can be expressed more simply as:

$$(t-a)^i = \sum_{k=0}^{i}(-1)^k\binom{i}{k}t^{i-k}a^k \qquad \text{(B.7)}$$

where the $\binom{i}{k}$ are the binomial coefficients:

$$\binom{i}{k} = \frac{n!}{k!(n-k)!} \qquad \text{(B.8)}$$

substituting into (B.5), and noting that the integral of a sum is equal to the sum of an integral:

$$\int_0^\infty p(a)\int_a^\infty (t-a)^i \frac{f_d(t)}{S(a)}dtda = \frac{1}{X(0)}\sum_{k=0}^{i}(-1)^k\binom{i}{k}\int_0^\infty a^k\int_a^\infty t^{i-k} f_d(t)dtda \qquad \text{(B.9)}$$

The inner integral:

$$\int_a^\infty t^{i-k} f_d(t)dt \qquad \text{(B.10)}$$

can be integrated by parts. Put:

$$\begin{aligned} u &= t^{i-k} \\ \frac{du}{dt} &= (i-k)t^{i-k-1} \\ \frac{dv}{dt} &= f_d(t) \\ v &= D(t) = 1 - S(t) \end{aligned} \tag{B.11}$$

using:

$$\int_a^\infty u\frac{dv}{dt}dt = [uv]_a^\infty - \int_a^\infty v\frac{du}{dt}dt \tag{B.12}$$

then:

$$\begin{aligned} &\int_a^\infty t^{i-k} f_d(t)dt = \left[t^{i-k} - t^{i-k}S(t)\right]_a^\infty - (i-k)\int_a^\infty t^{i-k-1}(1-S(t))dt \\ &= \lim_{t\to\infty}\left(t^{i-k} - t^{i-k}S(t)\right) - a^{i-k} + a^{i-k}S(a) - (i-k)\int_a^\infty t^{i-k-1}dt + (i-k)\int_a^\infty t^{i-k-1}S(t)dt \\ &= \lim_{t\to\infty}\left(t^{i-k} - t^{i-k}S(t)\right) - a^{i-k} + a^{i-k}S(a) - \lim_{t\to\infty}\left(t^{i-k}\right) + a^{i-k} + (i-k)\int_a^\infty t^{i-k-1}S(t)dt \end{aligned} \tag{B.13}$$

because $S(\infty) = 0$, this reduces to:

$$\int_a^\infty t^{i-k} f_d(t)dt = a^{i-k}S(a) + (i-k)\int_a^\infty t^{i-k-1}S(t)dt \tag{B.14}$$

substituting into (B.9):

$$\int_0^\infty p(a)\int_a^\infty (t-a)^i \frac{f_d(t)}{S(a)}dtda$$
$$= \frac{1}{X(0)}\sum_{k=0}^{i}(-1)^k\binom{i}{k}\left[\int_0^\infty a^k\left(a^{i-k}S(a)+(i-k)\int_a^\infty t^{i-k-1}S(t)dt\right)da\right] \quad \text{(B.15)}$$
$$= \sum_{k=0}^{i}(-1)^k\binom{i}{k}\left[\int_0^\infty p(a)a^i da + (i-k)\int_0^\infty a^k\int_a^\infty p(t)t^{i-k-1}dtda\right]$$

reversing the order of integration on the double integral gives:

$$\int_0^\infty p(a)\int_a^\infty (t-a)^i \frac{f_d(t)}{S(a)}dtda$$
$$= \sum_{k=0}^{i}(-1)^k\binom{i}{k}\left[\int_0^\infty p(a)a^i da + (i-k)\int_0^\infty p(t)t^{i-k-1}\int_0^t a^k dadt\right]$$
$$= \sum_{k=0}^{i}(-1)^k\binom{i}{k}\left[\int_0^\infty p(a)a^i da + \frac{(i-k)}{(k+1)}\int_0^\infty p(t)t^{i-k-1}\left[t^{k+1}\right]dt\right]$$
$$= \sum_{k=0}^{i}(-1)^k\binom{i}{k}\left[\int_0^\infty p(a)a^i da + \frac{(i-k)}{(k+1)}\int_0^\infty p(t)t^i dt\right] \quad \text{(B.16)}$$
$$= \sum_{k=0}^{i}(-1)^k\binom{i}{k}\left(1+\frac{i-k}{k+1}\right)\left[\int_0^\infty p(t)t^i dt\right]$$
$$= \sum_{k=0}^{i}\left[(-1)^k\binom{i}{k}\left(\frac{i+1}{k+1}\right)\right]\left[\int_0^\infty p(a)a^i da\right]$$

thus the integral contains no terms involving *k*, and may be separated from the sum. In order to prove (B.4), all that is required is to show that:

$$= \sum_{k=0}^{i}\left[(-1)^k\binom{i}{k}\left(\frac{i+1}{k+1}\right)\right] = 1 \quad \text{(B.17)}$$

to do this it is first noted that:

$$\binom{i}{k}\left(\frac{i+1}{k+1}\right) = \frac{(i+1)i!}{(k+1)k!(i-k)!}$$
$$= \frac{(i+1)!}{(k+1)!((i+1)-(k+1))!} \qquad \text{(B.18)}$$
$$= \binom{i+1}{k+1}$$

so that:

$$\sum_{k=0}^{i}\left[(-1)^k \binom{i}{k}\left(\frac{i+1}{k+1}\right)\right] = \sum_{k=0}^{i}\left[(-1)^k \binom{i+1}{k+1}\right] \qquad \text{(B.19)}$$

using the recursive relation for binomial coefficients:

$$\binom{i+1}{k+1} = \binom{i}{k} + \binom{i}{k+1} \qquad \text{(B.20)}$$

means that:

$$\sum_{k=0}^{i}\left[(-1)^k \binom{i+1}{k+1}\right] = \sum_{k=0}^{i}\left[(-1)^k \binom{i}{k} + (-1)^k \binom{i}{k+1}\right] \qquad \text{(B.21)}$$

to see that this must equal unity, the terms can be written out as:

$$\sum_{k=0}^{i}\left[(-1)^k \binom{i}{k} + (-1)^k \binom{i}{k+1}\right] = \binom{i}{0} - \binom{i}{1} + \binom{i}{2} - \dots + \binom{i}{1} - \binom{i}{2} + \dots$$
$$= \binom{i}{0} \qquad \text{(B.22)}$$
$$= 1$$

thus, all the terms of the sum cancel out, except the first, which is always equal to unity. Thus equation (B.17) has been proved, which means that (1.3.44), repeated below:

$$\int_0^\infty p(a)\int_a^\infty (t-a)^i \frac{f_d(t)}{S(a)}\,dtda = \int_0^\infty p(a)a^i da \qquad (1.3.44)$$

has been proved. Thus, the moments of life to come (averaging over times of death and current ages) are equal to the moments of life lived.

As the raw moments $E[t^i]$ can be used to determine the central moments $E[(t\text{-}E[t])^i]$, via:

$$E\left[(t-E[t])^i\right] = \sum_{j=0}^{i} \binom{i}{j} (-1)^{i-j} E\left[t^i\right](E[t])^{i-j} \qquad (B.23)$$

then it follows that the central moments of life to come are equal to the central moments of life lived. These relations are of interest because they give the variance, skewness and kurtosis, which are the second, third and fourth central moments respectively.

Appendix C. Description of Ferguson's Method for Estimating the Loss of Life Expectancy Resulting from Occupational Dust Exposures

Quarrying and coal mining are industries in which workers are exposed to mineral dust particles small enough to reach the lung alveoli. Such exposures can lead to lung diseases known as pneumoconioses. Each type of dust has a specific disease associated with it. The disease resulting from inhalation of coal dust is known as coal-worker's pneumoconiosis (CWP). The disease resulting from inhalation of stone is known as silicosis. Whereas it has been possible to estimate the effect of exposures to radiation and pollution by the use of response functions, it is not possible to use this approach for mineral dust, as the effect of exposures on life expectancy has not been adequately studied. It is known that, as with radiation, there is a long latency period between exposure and the associated impact. The number of annual deaths from CWP and silicosis is recorded in the national mortality statistics, as published by the ONS [151]. From these statistics, it is possible to produce a crude estimate of the loss of life expectancy caused by these diseases. However, those who are currently dying from this disease are likely to have been exposed to dust 20-40 years ago. To estimate the loss of life expectancy from those currently exposed to dust, it is necessary to perform extrapolations of the data. This method was originally used by Ferguson (1989) [83], and will now be described, although the method has been slightly expanded on here.

The national mortality statistics referenced above give detailed breakdowns of the number of deaths by age category and disease. From these statistics, the years of lost life for each death can be calculated. As the ages are delineated into groups of five years, it is necessary to assume that the age of death occurs in the mid-point of the group. The loss of life expectancy for an individual can be calculated crudely by assuming that, had the individual not died, he would have lived to age 85. Any individuals who die after this age are not included in the calculation. The average collective loss of life expectancy and average age at death for the whole group of deaths can then be calculated. Data is available for the nine years from 2001 to 2009, and so these quantities are calculated over this period. The trend for both CWP and silicosis is for decreasing average loss of life expectancy and increasing average age of death, although there is considerable fluctuation in both these trends. It is then possible to extrapolate a trend line to both of these quantities so that they can be estimated at any point in the future. As discussed by Ferguson, for the loss of life expectancy, a linear extrapolation is inappropriate, as it predicts a relatively rapid decline to zero. A more accurate trend line is an exponential extrapolation. For the average age of death, a linear extrapolation is appropriate. To estimate the collective loss of life expectancy from silicosis for quarrying activities only, it is necessary to multiply the silicosis estimates by 20%, which is the proportion of silicosis cases reported to the HSE under the Industrial Injuries Scheme, see HSE (2011a) [104]. The loss of life expectancy and age of death data is shown in Table 84 and Table 85. The trend lines are also shown Figure 51 and Figure 52. The trend lines for the silicosis data are a poor fit, as data is based on only a few fatalities, and there are large fluctuations. Nevertheless, they will be taken as providing a measure of the future loss of life expectancy and age of death from silicosis.

It is then possible to estimate the age of death and loss of life expectancy from current exposures to the workforce. The high value of the pneumoconiosis impacts will be assumed to be equal to the current loss of life expectancy estimated from the most recent five years. This value is 468 person-years for CWP and 14 person-years for silicosis. The low value can be estimated by finding the year in which the age of the current workforce is equal to the age of death from CWP and silicosis. The current average age of the workforce is about 41 years. Based on the extrapolations of the age of death, the members of this workforce who do die of pneumoconiosis, will do so at age 94 in the year 2062 for silicosis and age 108 in the year 2077 for CWP. These numbers appear to be quite high, and are not judged to be credible. The error results from the linear extrapolation of the age of death, which probably will not change quite as quickly. Another estimate can be made of the impacts by assuming that the age of death remains constant over time. In this situation those who die from silicosis will do so on average at age 79 in 2047, whilst CWP deaths will on average occur at age 83 in 2051. These numbers appear more reasonable. The collective loss of life expectancy extrapolated to these points is then 0.06 and 0.5 person-years respectively. These can then be normalised against current outputs of 87.3 Mt of coal and 1,122 Mt of stone. The impacts, in terms of years of lost life per Mt, are then 5.3×10^{-5} – 0.01 years/Mt for silicosis, and 0.01 – 5.4 years/Mt for CWP.

Collective Average Loss of Life Expectancy (person-years)	CWP	Silicosis	Silicosis Attributed to Quarrying
2001	1038	115	23
2002	1135	250	50
2003	883	60	12
2004	883	108	22
2005	745	65	13
2006	455	105	21
2007	370	40	8
2008	423	90	18
2009	348	48	10

Table 84 Collective loss of life expectancy from CWP and silicosis.

Average Age of Death	CWP	Silicosis
2001	80.4	78.4
2002	81.1	74.7
2003	81.5	81.6
2004	80.7	78.3
2005	81.2	78.1
2006	83.2	76.7
2007	82.9	81.8
2008	82.7	73.2
2009	83.8	83.8

Table 85 Average age of death for CWP and silicosis deaths.

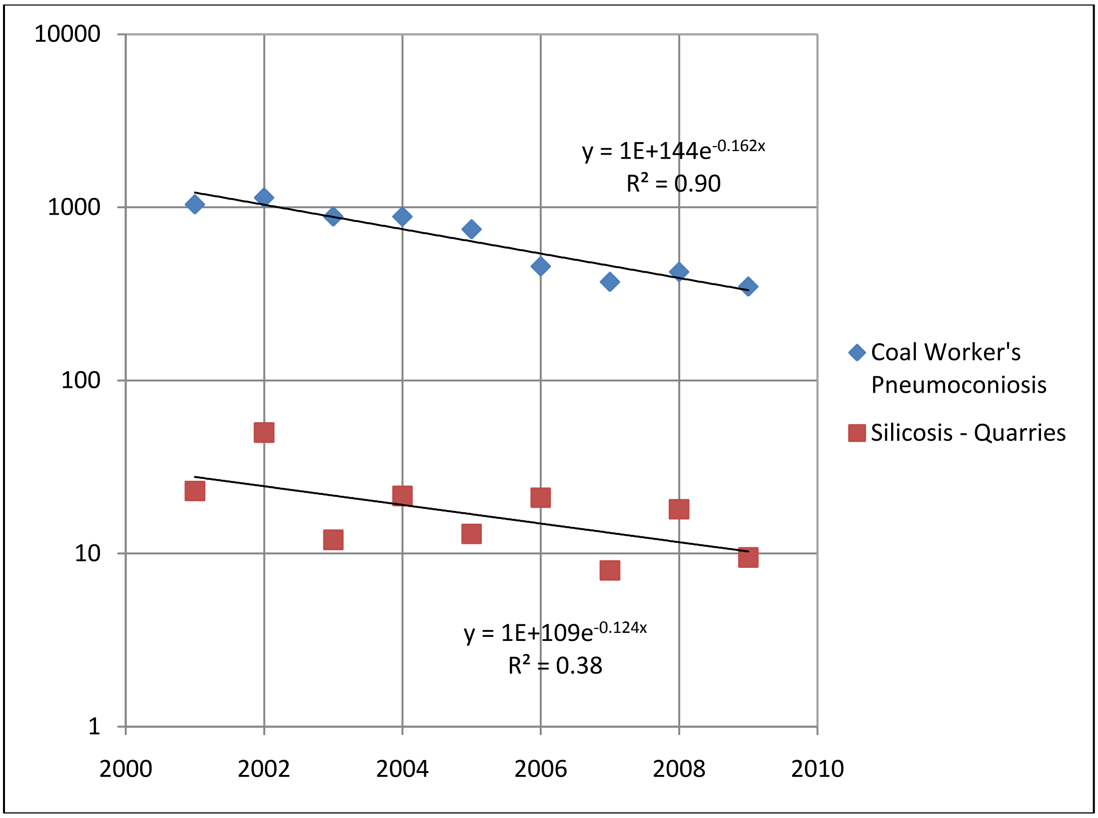

Figure 51 Exponential trend lines used in the extrapolation of the collective loss of life expectancy from CWP and silicosis.

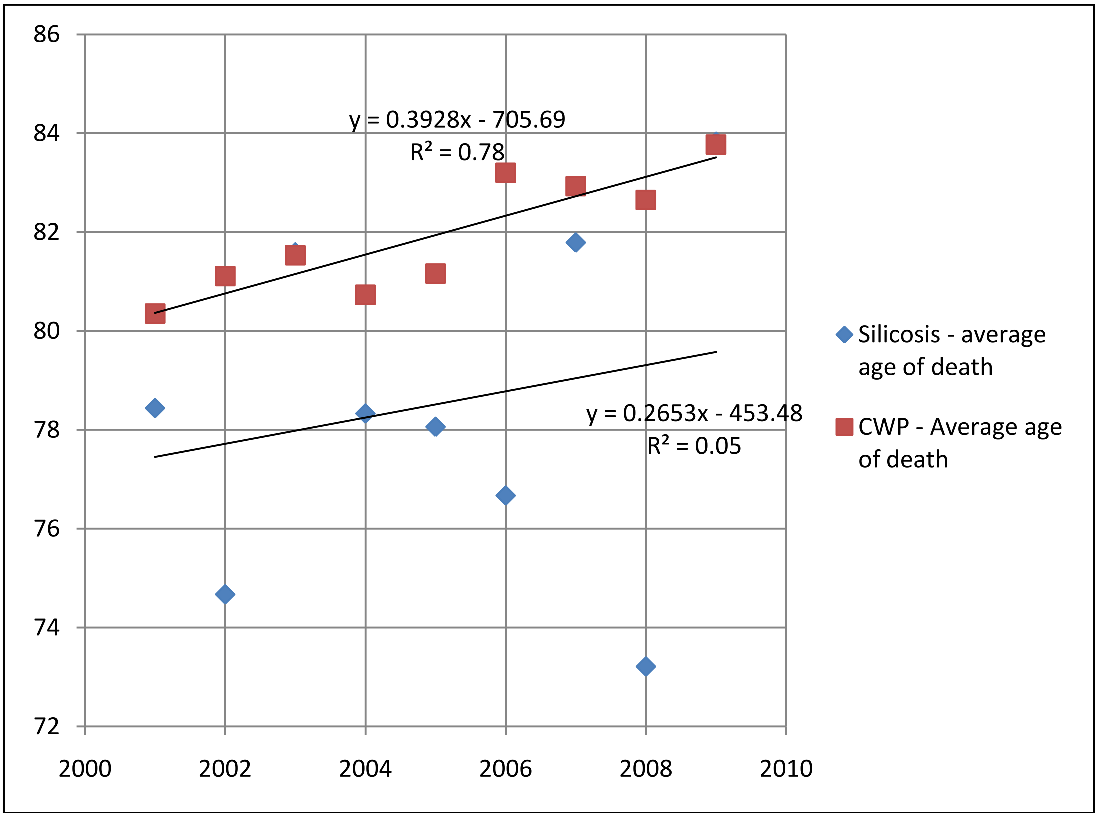

Figure 52 Linear trend lines used in the extrapolation of the average age of death from CWP and silicosis.

Appendix D. Energy Fatality Database and UK Electricity Generation Statistics

Table 86 lists all fatalities involved in the generation of electricity by the technologies studied. The time period over which the fatalities occurred was December 2005 to November 2010.

Table 87 lists the amount of energy generated and the capacity of the assessed electricity generation technologies in the UK. The annual capacity factor is also shown. The average hourly capacity for a given year is the average of the capacity for that year and the year before, multiplied by 8766, the number of hours in a year.

Table 88, Table 89 and Table 90 list UK production figures for gas, oil and coal. The electricity equivalent of such production is also shown.

Energy Type	Date	Fuel Chain Stage	Sub-Stage	Name	Facility	Location
Nuclear	09/07/2010	Power Plant	Operation	Chris Cowan	Heysham 1	Lancashire
Onshore Wind	22/05/2007	Power Plant	Construction	Basilio Brazao	Earlsburn	Stirlingshire
Onshore Wind	18/03/2008	Power Plant	Operation	Waldemar Neumann	Cefn Croes	Cardiganshire
Onshore Wind	16/09/2009	Power Plant	Operation	Colin Sinclair	Causeywaymire	Highland
Offshore Wind	12/11/2009	Power Plant	Construction	Gilbert Camacho	Greater Gabbard	Essex
Offshore Wind	21/05/2010	Power Plant	Construction	Per Terp	Greater Gabbard	Essex
Gas/Oil - Abnormal	27/12/2006	Extraction	Operation	Bob Warburton	North Morecambe Platform	Lancashire
Gas/Oil-Abnormal	27/12/2006	Extraction	Operation	Alfred Neasham	North Morecambe Platform	Lancashire
Gas/Oil-Abnormal	27/12/2006	Extraction	Operation	Leslie Ahmed	North Morecambe Platform	Lancashire
Gas/Oil-Abnormal	27/12/2006	Extraction	Operation	John Shaw	North Morecambe Platform	Lancashire
Gas/Oil-Abnormal	27/12/2006	Extraction	Operation	Simon Foddering	North Morecambe Platform	Lancashire
Gas/Oil-Abnormal	27/12/2006	Extraction	Operation	Steve Potton	North Morecambe Platform	Lancashire
Gas/Oil-Abnormal	27/12/2006	Extraction	Operation	Keith Smith	North Morecambe Platform	Lancashire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Paul Burnham	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Richard Menzies	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Brian Barkley	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Vernon Elrick	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Leslie Taylor	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Nairn Ferrier	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Gareth Hughes	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	David Rae	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Raymond Doyle	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	James John Edwards	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Nolan Carl Goble	Miller Oilfield	Aberdeenshire
Gas/Oil-	01/04/2009	Extraction	Decomm-	James Costello	Miller Oilfield	Aberdeenshire

Abnormal			issioning			
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Alex Dallas	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Warren Mitchell	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Stuart Wood	Miller Oilfield	Aberdeenshire
Gas/Oil-Abnormal	01/04/2009	Extraction	Decomm-issioning	Mihails Zuravskis	Miller Oilfield	Aberdeenshire
Gas/Oil	01/04/2009	Extraction	Operation	David Stephenson	Wellservicer Vessel	Aberdeenshire
Gas/Oil	23/09/2007	Extraction	Operation	Finlay Macfayden	Viking Islay Vessel	Yorkshire
Gas/Oil	23/09/2007	Extraction	Operation	Robert O'Brien	Viking Islay Vessel	Yorkshire
Gas/Oil	23/09/2007	Extraction	Operation	Robert Ebertowski	Viking Islay Vessel	Yorkshire
Gas/Oil	22/11/2009	Extraction	Operation	Stephen Allen		Fife
Gas/Oil	02/02/2009	Extraction	Operation	Michael Ford		West Lindsey
Gas/Oil	06/01/2007	Extraction	Construction	Matthew Grey	Bleo Holm Oil Rig	Aberdeenshire
Gas/Oil	07/10/2006	Extraction	Construction		Brent Charlie Platfrom	Aberdeenshire
Gas/Oil	20/02/2006	Extraction	Operation	Derrick Love	Seawell Platform	Aberdeenshire
Gas/Oil	11/11/2005	Extraction	Construction	David Soanes	Clipper Platform	Norfolk
Gas/Oil-Abnormal	12/04/2007	Extraction	Construction	Oddne Arve Remoy	Bourbon Dolphin Vessel	Shetland
Gas/Oil-Abnormal	12/04/2007	Extraction	Construction	Bjarte Grimstad	Bourbon Dolphin Vessel	Shetland
Gas/Oil-Abnormal	12/04/2007	Extraction	Construction	Kjetil Rune Vage	Bourbon Dolphin Vessel	Shetland
Gas/Oil-Abnormal	12/04/2007	Extraction	Construction	David Remoy	Bourbon Dolphin Vessel	Shetland
Gas/Oil-Abnormal	12/04/2007	Extraction	Construction	Frank Nygard	Bourbon Dolphin Vessel	Shetland
Gas/Oil-Abnormal	12/04/2007	Extraction	Construction	Ronny Emblem	Bourbon Dolphin Vessel	Shetland
Gas/Oil-Abnormal	12/04/2007	Extraction	Construction	Soren Kroer	Bourbon Dolphin Vessel	Shetland
Gas/Oil-Abnormal	12/04/2007	Extraction	Construction	Tor Karl Sando	Bourbon Dolphin Vessel	Shetland
Gas	30/08/2007	Power Plant	Operation	Michael Benn	Connah's Quay	Flintshire
Gas	06/10/2007	Preparation	Construction	Adrianus Van Hamm	South Hook LNG Terminal	Pembrokeshire
Gas	13/03/2008	Power Plant	Operation	Brian Collins	Sutton Bridge	Lincolnshire
Gas	26/11/2007	Power Plant	Construction	Christopher Longbottom	Uskmouth	Gwent
Gas	06/08/2005	Preparation	Operation	Neil Millar	Aldbrough Gas Storage	Yorkshire
Gas	18/01/2007	Preparation	Operation	Derek Barley	Byley Gas Storage	Cheshire
Coal	13/07/2005	Power Plant	Operation	Michael Robson	Eggborough	Yorkshire
Coal	28/09/2007	Power Plant	Operation	Alwyne Parkinson	Drax	Yorkshire

Coal	10/06/2007	Power Plant	Operation	Christopher Booker	Aberthaw	Vale of Glamorgan
Coal	31/07/2009	Power Plant	Operation	Stuart Hobbs	Aberthaw	Vale of Glamorgan
Coal	20/07/2007	Preparation	Operation	Alan Noddle	Immingham Dockyard	Lincolnshire
Coal	24/07/2009	Extraction	Operation	John Harbron	Thoresby Colliery	Nottinghamshire
Coal	18/10/2009	Extraction	Operation	Ian Cameron	Kellingley Colliery	Yorkshire
Coal	07/12/2009	Extraction	Operation	Jackie Fisher	Maltby Colliery	Yorkshire
Coal	30/09/2008	Extraction	Operation	Donald Cook	Kellingley Colliery	Yorkshire
Coal	24/01/2008	Extraction	Operation	Jim Griffin	Pennyvennie Mine	Ayrshire
Coal	03/11/2007	Extraction	Operation	Paul Milner	Welbeck Colliery	Nottinghamshire
Coal	26/02/2007	Extraction	Operation	Colin Ferguson	Pennyvennie Mine	Ayrshire
Coal	26/02/2007	Extraction	Operation	Brian French	Pennyvennie Mine	Ayrshire
Coal	17/01/2007	Extraction	Operation	Anthony Garrigan	Daw Mill Colliery	Warwickshire
Coal	07/08/2006	Extraction	Operation	Paul Hunt	Daw Mill Colliery	Warwickshire
Coal	20/06/2006	Extraction	Operation	Trevor Steples	Daw Mill Colliery	Warwickshire

Table 86 UK Energy fatalities between December 2005 – November 2010. Major data sources: [1], [42], [105], [106], [133].

	Capacity (MW)	**Average Hourly Capacity (GWh)**	**Generation (GWh)**	**Capacity Factor**
Onshore Wind				
2010	4,037	32,937	7,137	21.7%
2009	3,483	27,609	7,564	27.4%
2008	2,820	21,478	5,792	27.0%
2007	2,083	16,355	4,491	27.5%
2006	1,651	13,148	3,574	27.2%
2005	1,351		2,501	
Offshore Wind				
2010	1,341	9,997	3,046	30.5%
2009	941	6,689	1,740	26.0%
2008	586	4,292	1,305	30.4%
2007	394	3,055	783	25.6%
2006	304	2,267	651	28.7%
2005	214		403	
Gas - CCGT				
2010	32,209	271,941	170,708	62.8%
2009	29,878	256,103	162,244	63.4%
2008	28,593	243,191	171,631	70.6%
2007	26,930	236,060	152,084	64.4%
2006	26,965	233,936	129,248	55.2%
2005	26,445		142,481	
Nuclear				

2010	10,865	95,147	62,140	65.3%
2009	10,858	95,646	69,098	72.2%
2008	10,979	96,176	52,486	54.6%
2007	10,979	96,132	63,028	65.6%
2006	10,969	99,956	75,451	75.5%
2005	11,852		81,618	
Coal				
2010	23,085	202,190	107,694	53.3%
2009	23,077	202,119	103,038	51.0%
2008	23,069	201,817	124,381	61.6%
2007	23,008	200,998	135,944	67.6%
2006	22,882	199,329	148,850	74.7%
2005	22,627		130,690	

Table 87 UK generation of electricity by the assessed technologies. Data from [51].

UK Continental Shelf Natural Gas Production and Supply		
	Generation (GWh)	Output (GWa)
2010	664,353	75.8
2009	693,965	79.2
2008	809,649	92.4
2007	838,092	95.6
2006	929,784	106.1
2005	1,025,232	117.0

Table 88 UK production of natural gas [50].

UK Continental Shelf Oil Production		
	Production (Million Tonnes)	Output (GWa)
2010	63.0	30.9
2009	68.2	33.4
2008	71.7	35.1
2007	76.6	37.5
2006	76.6	37.5
2005	84.7	41.5

Table 89 UK production of oil [48].

UK Coal Production		
	Production (Million Tonnes)	Output (GWa)
2010	17.7	5.4
2009	17.4	5.3
2008	17.6	5.4
2007	16.5	5.0
2006	18.1	5.5
2005	20.0	5.9

Table 90 UK production of coal [48].