Sustainability Assessment of Nuclear Power in the UK Using an Integrated Multi-Criteria Decision-Support Framework

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Abstract

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In the UK, the debate surrounding energy production lies at the forefront of the political agenda, with growing emphasis on achieving an increasingly sustainable energy mix into the future. The nuclear option is especially debatable - issues such as waste management and decommissioning receive much attention. In addition, the many stakeholders interested in nuclear power display very divergent views on its sustainability. Since the turn of the century, nuclear power has received much attention globally, with many nations' governments taking consideration of the potential benefits of new nuclear adoption. Conversely, the Fukushima nuclear disaster has led to new nuclear resistance in other nations, such as Germany, where plans have been made to stop nuclear power generation completely. This research aims to help inform the debate on nuclear power and the future UK electricity mix. A multi-criteria decision support framework (developed by the SPRIng Project) has been used for these purposes, taking into account technical, economic, environmental and social criteria.

The methodology used in this work has involved: stakeholder consultation; use of future electricity scenarios; sustainability assessment of current and future electricity options (Pressurised Water Reactor, European Pressurised Reactor, European Fast Rector, coal, gas, solar and wind power, and coal carbon capture and storage [CCS] power); assessment of future electricity scenarios based on both sustainability impacts and stakeholder (expert and public) preferences for the sustainability indicators and electricity technologies. The sustainability assessment of future nuclear power options and coal CCS power have been carried out here for the first time in a UK-specific context.

Based on the public and expert opinions on the importance of different sustainability indicators, results of the scenario analysis suggest that the scenario with a high penetration of low-carbon technologies (nuclear [60%] and offshore wind power [40%]) is the most sustainable. For the sample considered in this study, this finding is not sensitive to different stakeholder and public opinions on the importance of the sustainability indicators. However, when the stakeholder preferences for individual technologies are considered, scenarios with high penetration of renewables (26-40% solar and 20-48% wind) become the preferred options. This is due to the favourable stakeholder opinion on solar and wind power. In that case, the scenario with high penetration of nuclear is never the preferred option due to the low to moderate stakeholder preference for nuclear power.

Therefore, the results from this research suggest that the 'sustainability' of different electricity options and scenarios is highly dependent on stakeholder preferences and priorities. Thus, for successful future deployment of these options and implementation of energy policy measures, transparency of information on the impacts of electricity options is key in ensuring that stakeholder opinions are founded in the actual rather than the perceived impacts of these options.

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1 Introduction

The concept of sustainable development is often defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). The World Commission on Environment and Development report, 'Our Common Future', or the Brundtland Report as it is more commonly known, was written in 1987 and was one of the first of its kind to recognise the importance of integrating economic, environmental and social sustainability issues (also known as the 'three pillars of sustainability'). The report recognised that economic growth occurs largely at the expense of the environment, due to unsustainable consumption of resources and the mismanagement of waste materials:

> "Environmental stress has often been seen as the result of the growing demand on scarce resources and the pollution generated by the rising living standards of the relatively affluent." (WCED, 1987)

The challenge for sustainable development today lies in the ability to 'solve' the dichotomous relationship between economic growth and environmentally benign practices, whilst meeting the needs of the world's population. This challenge includes decisions regarding energy policy, which has been thrust to the forefront of the international and UK political agenda largely due to the environmental, economic and social impact concerns related to energy production and climate change (DTI, 2006b; DTI, 2007; BERR, 2008; DECC, 2009; DECC, 2010; DECC2012a).

A full sustainability appraisal of all energy options is necessary to determine which technologies perform best with regard to their economic, environmental and social impacts. This includes the nuclear option which had been favoured by the previous UK's Labour Government and continues to be on the agenda of the current Coalition Government who stated that "*we have agreed a process that will allow Liberal Democrats to maintain their opposition to nuclear power while permitting the government to bring forward the national planning statement for ratification by parliament so that new nuclear construction becomes possible*" (WNN, 2010). Even after the Fukushima incident of 2011, the UK's position on nuclear power remains unchanged.

The UK has a long history of nuclear power generation, which began with the world's first commercial nuclear power reactor – Calder Hall-1, located at the modern Sellafield site in Cumbria, which began generation in 1956. UK interest in the progression of research surrounding nuclear fission before this time was primarily focussed on the development and testing of nuclear weapons through the extraction of plutonium from spent uranium fuel. The United Kingdom, along with Canada and the United States of America, developed the Manhattan Project, which ultimately led to the first and only atomic bombings in history – those of Hiroshima and Nagasaki in Japan, 1945.

In spite of the terrible consequences of the atomic bombings carried out on Japan, many Western governments were keen to exploit the potential benefits of nuclear fission after the end of the Second World War. The UK's nuclear power programme continued to expand from this time, and the United Kingdom Atomic Energy Authority (a statutory agency) was charged with overseeing nuclear energy development in the UK from 1954. Until 1996, the nuclear industry and therefore all of the UK's nuclear power plants, were government-owned, though British Nuclear Fuels Limited (BNFL) (WNA, 2013a). At this time, the UK government privatised the nuclear power industry and in 1997, power generation from nuclear power as a proportion of total UK electricity generating reached its peak at 26% – it has declined since then, as old reactors have been shut-down (WNA, 2013a). It is only since 2006 that the previous Labour Government began the process in which new nuclear build would be considered for the UK (WNA, 2013b).

The UK's history with regard to its nuclear power programme has not been adversely impacted from significant nuclear accidents on UK soil. Three accidents have occurred in the UK since nuclear generation began: Windscale Pile, 1957 (International Nuclear Event Scale [INES] level 5); Chapelcross, 1967; and Sellafield, 2005 (INES level 3) (The Guardian, 2011). The INES scale begins at level 0 (the least serious event, classed as a deviation), to level 7 (major accident – the most serious event). These accidents have involved two fires (in the case of the Windscale and Chapelcross incidents) and a plutonium leak from Thorp nuclear fuel reprocessing plant (The Guardian, 2011). It should be noted that these events are associated with reactor management, rather than caused by external factors (such as earthquakes, which the UK is not particularly sensitive to).

Although nuclear accidents (domestic and international) have not had a significant influence on government decision-making with regard to the UK nuclear power programme, no new nuclear reactor has been constructed in the UK since Sizewell B in 1987, despite plans being made for further PWRs in addition to this (these included a potential Hinkley Point C, Wylfa B and Sizewell C) (WNA, 2013a). This was largely down to a government decision to privatise the nuclear industry and provide no further subsidies for power generation from nuclear sources from the public purse. Current UK policy towards nuclear power is one of support, with market incentives, such as Electricity Market Reform (Contracts for Difference and Capacity Market), which aim to make nuclear power in the UK an attractive investment to private companies (WNA, 2013b).

In recent years, an increasing global energy demand, climate change and security of fuel supply are all factors that have enabled a global ‘nuclear renaissance’. Countries with rapid nuclear expansion programmes include China and India. China has built ten nuclear power plants over the last few years and 26 more are currently under construction. India plans for an additional 20-30 reactors to be built by 2020 (WNA, 2013c). Clearly, these are ambitious targets, although a fast-paced growth of population size in both of these countries and energy demand from manufacturing are key drivers to a rapid nuclear expansion. The Fukushima nuclear disaster of 2011, in Japan, appears to have had little negative impact on political decision making with regard to the nuclear power programmes in both nations.

Conversely, in Germany, the environmental movement amongst citizens there has led to the government to push through plans to shut down all of its commercial nuclear reactors due to fears over safety and environmental damage from potential accidents.

Such issues highlighted in the above paragraphs highlight the significance that different stakeholders and decision makers may have on influencing energy policy in different nations. In spite of the recent continued support from the UK government on nuclear power policy, numerous issues still need to be resolved before new nuclear power plants are built and decommissioned. In addition, potential stakeholder and decision maker sensitivities to nuclear power expansion also need to be explored. Sustainability issues include safety and security of nuclear power, waste and decommissioning, and economic risk of investing in nuclear power (BERR, 2008). As a result of the significance of these issues, the sustainability of nuclear power is under scrutiny, with many believing that alternatives to nuclear power provide better, more sustainable options for meeting our energy needs (Greenpeace, 2005; NFLA, 2006; Roche, 2005). Due to the complex issues associated with new nuclear build, an evaluation of its viability in the UK's energy mix will need to take into account conflicting interests in a transparent and structured way. This research aims to contribute towards this goal.

The overall aim of the work is to assess the sustainability of nuclear power in an integrated UK electricity mix, applying an integrated multi-criteria decision support framework. The framework is holistic in nature, with the full life cycle environmental, economic and social impacts of electricity technologies and future electricity scenarios being taken into account, in addition to stakeholder (expert and public) views through the application of multi-criteria decision-analysis. Integration of these tools (life cycle assessment for environmental impact assessment and multi-criteria decision-analysis to model stakeholder opinion) and methods, such as scenario analysis and life cycle economic and social impacts assessment, allow for more robust and comprehensive decision-making in the face of numerous and conflicting criteria and divergent stakeholder opinion. The specific objectives of this thesis include:

- development and application of a methodology for stakeholder engagement;
- sustainability assessment of nuclear and other electricity options up to 2070;
- sustainability assessment of different electricity scenarios for the UK up to the year 2070;
- multi-criteria decision-analysis of the findings of the sustainability assessments taking into account stakeholder preferences.

The decision-support framework applied here has been developed as part of the SPRIng project (see Azapagic *et al.*, 2011). The framework enables comparisons of different electricity options and future scenarios using relevant sustainability criteria. A number of potential future scenarios have been developed to allow identification of the most sustainable electricity mix, depending on possible futures of electricity options. The framework is underpinned by life cycle thinking and multi-criteria decision-analysis (MCDA). Further detail on the methodological approach developed and used in the project can be found in Chapter 3. Chapters 4-8 present and discuss how the framework has been applied including stakeholder engagement and consultation; sustainability assessment of nuclear and other electricity technologies; and sustainability assessment of future electricity scenarios, respectively. The work is concluded and future work outlined in Chapter 9.

Prior to that, Chapter 2 reviews existing sustainability assessment frameworks that have been applied to energy systems. The stakeholder participatory process applied in some of these frameworks is also discussed, as a pretext to the methodological developments in this research.

The SPRIng Project

This PhD project was carried out as part of the SPRIng project. SPRIng was a consortium project funded from 2008-2011 by the Engineering and Physical Sciences Research Council (EPSRC) and Economic and Social Research Council (ESRC). The main aim of the SPRIng project was to develop a decision-support framework for assessing the sustainability nuclear power in an integrated UK energy mix. The framework takes into account economic, environmental, social and technical issues. This PhD work focused on the application of the SPRIng decision-support framework, as discussed in further detail in Chapter 3. The SPRIng decision-support framework consists of a number of steps, including: stakeholder input, identification of possible energy scenarios, sustainability assessment, multi-criteria decision-analysis of energy scenarios and technology options, and finally, recommendations based on this analysis. The aim of the SPRIng decision-support framework is to allow decisions on future electricity and nuclear power policy to be made in a rational and integrated manner (i.e. taking account of the full range of impacts associated with power generation, whilst also taking into account expert and public opinion). The work carried out as part of this PhD has added value to this approach by developing the framework at specific steps (namely: stakeholder engagement and analysis, sustainability assessment and future energy scenario assessment). In addition, an integrated assessment of future electricity scenarios and the role of nuclear power have been carried out.

2 Review of Sustainability Assessment Frameworks for Energy Systems and the Stakeholder Participatory Process

2.1 Introduction

This chapter reviews sustainability assessment frameworks already existing in literature, focusing on those developed for the energy sector specifically. Section 2.2 focuses on generic sustainability assessment frameworks: frameworks used to assess single dimensions of sustainability and integrated assessment frameworks, respectively. Sustainability indicators are reviewed as a method for framing complex decision-making problems in the energy field in Section 2.3. Section 2.4 reviews MCDA methods used in decision-making processes. Finally, Section 2.5 explores stakeholder participation in the decision-making process and how stakeholder values can be incorporated into decision-making problems and frameworks.

2.2 Frameworks for the Assessment of Sustainability

Many sustainability appraisals have been developed for all aspects of energy generation, which vary widely in their application and temporal and spatial extent. The simplest of these frameworks focus on one dimension of sustainability, economic, environmental or social. The evolution of sustainability assessment has seen efforts to integrate the three dimensions of sustainability into a common assessment framework for various energies (for example, IER, 2005; Madlener *et al.*, 2007; Granat and Makowski, 2006). Multi-criteria decision-support frameworks which consider relevant sustainability criteria applicable to nuclear and non-nuclear energy are rare and to date only one such framework has been found in literature (Roth et al., 2008). However, no such framework is available for the UK conditions, apart from a recently developed set of sustainability indicators for nuclear and other power options in the UK (Stamford and Azapagic, 2011; 2012). It is necessary to use a framework specific to UK conditions for several reasons. Firstly, certain sustainability issues may be more or less relevant in the UK compared to other nations. For example, this may include the likely occurrence of natural disasters or terrorist attacks that could affect the sustainability of nuclear power. Secondly, the nature of decision-making varies across nations and the interplay and significance of different stakeholders will have an effect on the decision-making exercise. Thirdly, country-specific data are needed in order to carry out a sustainability assessment of the techno-economic, environmental and social impacts of electricity technologies and future electricity scenarios. For example, data used to model the life cycle environmental impacts of electricity technologies should take into account processes and materials that would be used in the UK to build, operate and decommission power stations and other electricity-generating installations. Inputs, such as electricity used in order to carry out certain processes vary significantly from county to country.

Multi-criteria decision-analysis (MCDA) approaches and tools allow the diverse, complex and conflicting information inherent in multi-criteria decision-making problems to be organised and synthesized in such a way that all criteria can be taken into account (Belton and Stewart, 2002). MCDA is now recognised as a valuable application in any approach to determine environmental burdens or sustainable alternatives (Azapagic and Perdan, 2005a; French and Geldermann, 2005). This practice has been carried out increasingly since the recognition of its applicability to environmental problems (Munda, 1995). Keefer *et al.* (2004) identified that environmental risk in relation to the energy sector has been evaluated using MCDA as far back as 1992 (see Balson *et al.*, 1992). MCDA literature existing before this date with regard to the energy sector has mainly focussed on bidding, product and site selection, regulation, and technology choice (Corner and Kirkwood, 1991).

The evolutionary trend of MCDA use with regard to environmental problems is one of continued integration of stakeholders, uncertainties, multiple and conflicting criteria and extended temporal impacts (French and Geldermann, 2005). Therefore, problems of an environmental or ‘sustainable’ nature can be defined as multiple criteria decision making (MCDM) problems, due to multiple and often conflicting aspects that need to be considered simultaneously (Belton and Stewart, 2002).

MCDA is therefore well suited for ‘difficult’ decision problems and is appropriate to use in the context of nuclear power. The following section (2.2.1) details the trend from more simplistic decision-support frameworks to frameworks that integrate all three dimensions of sustainability.

2.2.1 Sustainability assessments: single dimensions of sustainability and integrated assessment frameworks

2.2.1.1 Economic frameworks

Many sustainability assessments which assess only one aspect of sustainability (economic, environmental or social aspects) employ differing methodologies in their assessments, meaning that the results of these appraisals cannot be aggregated in an easy and transparent way. The most prominent of these kind of sustainability assessments in literature are economic assessments, which are often used in order to 'screen' various technologies or systems before a more detailed assessment is carried out. Environmental and social assessments can often be much more complex than economic assessments, with qualitative as well as quantitative measures used in the evaluation (Singh *et al.*, 2009). Therefore, it is hard to compare the impacts of these measures when they are often assessed on varying scales of measurement. This had led to a trend of economic assessments which integrate environmental and social impacts (externalities) onto a monetary scale. This makes the evaluation process somewhat easier, in that comparisons can be made across impacts and trade-offs can easily be applied. However, this particular method has been widely criticised on the grounds that social injustice or environmental degradation cannot be solved purely by economic intervention (Spangenberg, 2005).

As previously stated, there are many economic assessment frameworks of energy technologies and systems already existing in literature. Here, the merits and disadvantages of these assessments applied to the nuclear energy sector are discussed.

The body of literature which seeks to appraise nuclear energy economically can be split into two fields: specific assessments where a particular process or technology is being assessed (for instance, Kunsch and Fortemps, 2002; Squarer *et al.*, 2003; Tian, 2001; Tian and Wang, 2001; and; Tian *et al.*, 2005), and those which are more generic and seek to compare nuclear to other electricity generating technologies or even other energy technologies (such as, Bohringer *et al.*, 2002; and; Juanico *et al.*, 2002).

In addition to the specific aims of economic assessments which are carried out on nuclear power, each assessment may also employ divergent or varying methodologies in their evaluation. For example, an economic assessment framework may consist of relatively simple economic performance parameters and cost data (aggregated into a capital value) (Tian and Wang, 2001), cost-benefit analysis (Tian *et al.*, 2005), or a more complex Fuzzy Inference Schemes (FIS) (Kunsch and Fortemps, 2002). This trend to more complex decision-support methods may be attributed to the decision problems becoming increasingly complex and uncertain. For example, Tian and Wang (2001) incorporate relatively few uncertainties into their framework by varying discount rate, fuel price and investment level after the initial cost assessment has been carried out. On the other hand, Kunsch and Fortemps' methodology to assess the cost of radioactive waste management (2002) harbours many more uncertainties, due to the fact that this stage in the life cycle of nuclear power generation has not been fully carried out (and therefore costed) and due to the large temporal scale involved with disposing of nuclear waste. Therefore, the assessment framework must encompass many uncertainties and contingency factors, to which fuzzy logic, or more specifically, a Fuzzy Inference Scheme may be applied. This framework represents one of the more 'integrated' examples found in literature, where decision aid (such as fuzzy logic) is used to address complex problems with many uncertainties.

2.2.1.2 Environmental frameworks

Many environmental assessment frameworks in literature do no attempt to integrate the results of their evaluations into a decision-support model, particularly in research surrounding energy technologies, much of which focuses on life cycle environmental burdens (e.g. Say *et al.*, 2007; Styles and Jones, 2008; Desideri *et al.*, 2012; Cao and Pawlowski, 2013). Moreover, many environmental life cycle assessments (LCA) exist that consider only one or two environmental aspects, such as greenhouse gas emissions or land use (Kelly *et al.*, 2012; Cao and Pawlowski, 2013).

As far as the author is aware, there is only one framework in literature which incorporates the environmental burdens of energy systems into a sustainability framework using environmental criteria alone (see Pietrapertosa *et al.*, 2009). The research integrated data using LCA, the ExternE (described later in this chapter) approach (internalising non-monetary burdens into capital value) and partial equilibrium models to determine the most cost-effective environmental strategies for the oil mining industry. As indicated in the next section of this chapter, applying costs to externalities (like environmental impacts) is not always useful when trying to understand the 'true' impacts of various energy technologies. Therefore, it is necessary to develop an environmental assessment framework of indicators within a larger, multi-criteria decision-support framework in order for conflicting objectives amongst stakeholders to be recognised and through which the appropriate trade-offs can be made.

2.2.1.3 Social frameworks

Many of the social assessments of energy technologies and systems found in literature are also associated with some element of economic assessment. This is due to the cross-over of many social factors into economic factors and measurements also. For example, health and safety fines and employment can have a monetary value placed on them relatively easily. Therefore, many social assessments encompass some element of economic evaluation (e.g. Mizuo, 2008). In addition to the link between social and economic impacts of a system or technology, there may also be 'fuzzy' boundaries between some social and environmental impacts, such as radionuclide contamination, which can be an environmental impact by related to the effects on the surrounding land and biodiversity, but it would also be classed as a social indicator when evaluating the effects on any inhabitants of the area (e.g. Garcez and de Souza Vianna, 2009).

In addition to the cross-over of some social criteria to some economic and environmental measures, the evaluation of energy technology impacts on society is also complicated by the varying scales of measurement of social sustainability indicators. In addition to each criterion or indicator usually being measured on discrete measurement scales, some criteria may be accounted for quantitatively as physical measures (for example, radionuclide contamination and living restrictions in a contaminated area), others are based on individuals' perceptions and behaviour and are measured on a qualitative or binary scale.

The history of social sustainability assessments is not as long as that of economic or environmental assessments. Social assessments have entered industry via Corporate Social Responsibility (CSR) reporting, which is largely self-regulatory. The lack of standards or legislation means that these measures cannot readily be used in industry or technology comparisons (Streimikiene *et al.*, 2009). In addition, CSR reports focus more heavily towards environmental degradation and protection, rather than societal impacts (Azapagic and Perdan, 2000).

In academic literature, there are also relatively few assessments focussing on social sustainability alone, and even fewer applied to the nuclear field. Furthermore, there are few empirical studies focussing on social impacts of energy systems and technologies, with many papers being largely descriptive/theoretical in nature (Garcez and de Souza Vianna, 2009; Shackley *et al*., 2009; and; Streimikiene at al., 2009). Mizuo (2008) has made one of the only attempts found in literature to develop a social assessment framework for nuclear power. The framework proposed is based upon communication of the 'four responsibilities' of nuclear power, legal, economic, environmental and social to all stakeholder groups involved with nuclear power generation. This framework approach does not propose a formal evaluation method to assess and compare a range of technologies, although it does provide information on social assessment criteria for a sustainability assessment. The only other attempt that this author is aware of is the paper by Roth, *et al.* (2009), which outlines an 'approach to the evaluation of sustainability of current and future electricity supply options'. As part of the methodology, the authors include social aspects of sustainability into their assessment, which include: energy security; political stability; social development; social aspects of risk; impact on landscape and residences; and impact on human health. This approach does propose a formal evaluation method to assess a variety of electricity options (including nuclear, coal, gas, hydro, wind, CHP and solar), which includes the use of MCDA by stakeholders to weight the indicators and the use of future scenarios to explore the impacts of a verity of electricity supply portfolios. The indicators used within this assessment are monetised using a total costs approach.

Other social assessment frameworks in the energy field are, as previously stated, very limited. One of the few examples has focussed on wind farm location (Gamboa and Munda, 2007). Although a multi-criteria evaluation has been used as part of the assessment, all of the indicators are given quantitative values and do not represent a comprehensive list of social considerations that would need to be included in a social evaluation. In addition, the method by which the criteria are scored for each alternative wind farm location is relatively simple in that it is based on an aggregation of the quantitative values given to each criterion.

It is clear from the literature that social indicators differ markedly in their nature from economic and environmental indicators which, broadly speaking can be dealt with in a more straightforward way when being integrated into a multi-criteria decision-support framework. The only attempt to integrate nuclear power and social indicators into a MCDA framework identified in this review is the methodology proposed by Roth *et al.* (2009). Special considerations need to be taken when valuing societal decisions due to ethical issues and problems relating to the valuing of opinions on certain criteria or indicators.

2.2.1.4 Integrated assessment frameworks

Integrated assessments encompass economic, environmental and social criteria into their assessment framework. It has become much more common for such assessments to be carried out in the last few years, as opposed to assessments which take into account one or two dimensions of sustainability. This change assists decision-makers in making balanced and transparent decisions regarding the sustainability of their system or technology. Trade-offs can be made by comparison of criteria in all three categories. In the case of separate economic, environmental and social assessment of a system, criteria and their relative values may not be compared and traded-off as readily as those in an integrated system. Also, the integration of economic, social and environmental indicators means that information regarding the sustainability of a system or process within a country can be conveyed easily to policy makers and other stakeholders.

However, despite the anticipated transparency of integrated sustainability assessments, many assessments may still be open to bias. The recommendations taken from an integrated sustainability assessment are only as good as the intrinsic subjectivity in the decision-makers' values. In turn, quantitative values calculated in the framework that are based on decision-makers' subjective values may deceptively depict complete objectivity, as they are not always presented in a transparent way. An integrated assessment of an energy system or process may not demonstrate the true sustainability of that system if it is not compared with others on the same basis.

Integrated sustainability assessments have been carried out both within academic and industrial projects. Typically, the academic projects tend to follow to 'top-down' approach to building the assessment framework whereby the framework and indicators used within the framework are developed by the researchers involved in the project (e.g. Afgan and Carvalho, 2002; Afgan and Carvalho, 2004; May and Brennan, 2006; Akella *et al.*, 2009; Begic and Afgan, 2007). Conversely, industrial projects have a propensity to use the bottom-up approach, where key stakeholders are used to build the framework and develop the sustainability indicators (Singh *et al*., 2009; Roth *et al.*, 2009; SPRIng, 2011).

Although there are many 'integrated' sustainability assessments found in literature (e.g. Afgan and Carvalho, 2002; Afgan and Carvalho, 2004; May and Brennan, 2006; Akella *et al.*, 2009; Begic and Afgan, 2007; Burton and Hubacek, 2007; Dinca *et al.*, 2007; Kone and Buke, 2007; Madlener *et al*., 2008; and; Jovanovic *et al.*, 2009), many of these do not represent a truly integrated framework. There are many aspects to an integrated framework which assesses the sustainability of energy systems. These include stakeholder engagement to identify their main sustainability issues, development of environmental, economic and social sustainability indicators to reflect these issues, sustainability assessment of different energy technologies and scenarios and multi-criteria decision-analysis (Azapagic *et al.*, 2011). Many of the academic approaches to assessing sustainability, or more specifically, energy system sustainability, only incorporate some of the above elements in their frameworks. For example, in many of the assessments, stakeholders have not been consulted in the process of building the framework. Some frameworks use future energy scenarios (e.g. Jovanovic *et al.*, 2009), while others rely on only the sustainability indicators to evaluate the system (e.g. Begic and Afgan, 2007).

Many of the papers mentioned above use MCDA as part of the assessment process. However, as stakeholders are not consulted regarding the selection on sustainability criteria or indicators, the 'true' sustainability cannot be revealed as stakeholders' values are not taken into account comprehensively or at all. In addition, many of the papers that have used MCDA as part of their framework are technology specific (i.e. not generic enough to be applied outside of their experimental field) (see McDowell and Eames, 2007), and others are theoretical and cannot be applied empirically (for example, Buchholz *et al.*, 2007; Elghali *et al.*, 2007).

The most comprehensive research studies/projects with regard to the assessment of the sustainability of energy systems are defined as those which are generally more generic in their applicability to energy systems and iterative in nature with the integration of stakeholders throughout the problem structuring, problem analysis and resolution process (Azapagic and Perdan, 2005a&b). Examples include the Artemis (Madlener *et al.*, 2007; Kowalski *et al.*, 2009), the ExternE (IER, 2005) and the NEEDS (Granat and Makowski, 2006) projects.

These projects are indeed very comprehensive in their approach to assessing the sustainability of different energy options. The overall aim of the Artemis project was to assess the sustainability of renewable energy technologies, specific to Austria, using future energy scenarios at the national and regional/local level. The methodology incorporates LCA, a participatory process and MCDA and incorporates non-renewable energy options into the framework. The ExternE project's overall aim was to identify the 'true' costs of electricity generating options, specific to European conditions. The methodology attributes monetary values to environmental and social impacts of electricity generating options, meaning that an overall 'cost' can be attributed to each option, and therefore options may be ranked in terms of their 'costs'. The method is based on the 'polluter pays' principle (OECD, 2001) and the results are largely site-specific, as an impact-pathway approach is employed in identifying the impacts. The NEEDS project represents an extension of the ExternE project (Granat and Makowski, 2006), with the aim of improving the valuation methodology. Other new aspects to this project include the incorporation of MCDA, life cycle assessment as well as the impact-pathway approach and the use of future energy scenarios by which to assess and compare electricity options.

Although the methodologies developed in these three projects are very comprehensive, they are not suitable for assessing the sustainability of nuclear power in an integrated UK electricity mix. This is because the criteria and scenarios used in the Artemis framework were developed with only renewable technologies in mind. In addition, the energy scenarios extend only to 2020, a rather short term given the importance of long-term thinking with respect to energy systems and particularly nuclear power. Similarly, the ExternE methodology makes it difficult to apply across EU nations due to its site-specific approach. Although the project was EU-based, the data used in the ExternE methodology are based on the average of data from the 15 EU nations, meaning that conditions in any given European country may differ from those specified in ExternE. In addition, the transparency of the framework is low as it is unclear how the single cost values for different technologies have been calculated. Also, as stated earlier, economic intervention cannot negate all negative environmental and social impacts nor can they necessarily be monetised. Furthermore, the NEEDS methodology, despite the updates and improvements, still suffers from the same issues as the ExternE methodology, notably the internalisation of external social and environmental impacts into monetary values. Furthermore, researchers' and experts' values have already been placed on the sustainability criteria by assigning them costs without the involvement or participation of any stakeholders.

2.3 Sustainability Indicators and Problem Sensitivities

This section reviews the use of sustainability indicators in sustainability assessment frameworks found in literature, with a focus on those developed for the energy sector (although some generic sustainability indicator sets are also considered). Section 2.3.1 begins by briefly reviewing sustainability indicators use in decision-support frameworks. Section 2.3.2 then goes on to describe the use of indicator sets that consider wider sustainability issues as part of a decision-support methodology.

2.3.1 Sustainability indicators

The use of sustainability indicators has been initiated as a means to measure the relative sustainability performance of various processes, systems or technologies. It is now widely agreed that sustainability assessments must incorporate economic, environmental and social dimensions. However, there is still no agreement regarding the extent of economic viability, social acceptability and environmental savings that should be achieved in order to deem something 'sustainable' (Azapagic and Perdan, 2000). Therefore, indicator sets which seek to determine the 'level' of sustainability are endorsed internationally as a necessary method to carry out these assessments (UNCED, 1992). This implies that appropriate sustainability indicators are needed to enable various levels of assessment of sustainability. These 'levels' may refer to a spatial context, or a governance context. For example, micro-sustainability studies may focus on the sustainability impacts of a single power plant. Macro-studies may seek to assess to overall sustainability of a particular energy technology in a nation. In addition, these assessments may be implemented at various levels; by local community groups, industry, national governments or international organisations (Azapagic and Perdan, 2000).

Although generic sets of indicators are useful as a standardised approach to assess sustainability to enable comparisons of sustainability (Azapagic and Perdan, 2000), their use is not always relevant across different ‘levels’ of assessment. Industry indicators have undergone a transformation over the last ten years (as has sustainability reporting as a whole), shifting from a level of concern targeted at environmental welfare, to an all-encompassing ‘three tier’ approach to sustainability (Azapagic and Perdan, 2000). Examples of integrated indicator sets applicable to industry include those developed by Azapagic and Perdan (2000), Azapagic (2004), Fernandez-Sanchez and Rodriguez-Lopez (2010) and Onat and Bayar (2010), Stamford and Azapagic (2011; 2012. Companies such as Royal Dutch Shell, DuPont and P&G in the chemical industry have also notably taken their own corporate initiatives in improving their company sustainability records (Azapagic and Perdan, 2000). Although many sustainability assessment indicators and frameworks are focussed towards industry (as their impacts are widespread and wide-ranging), wider initiatives have also come to the fore in recent years. The most notable of these has arguably been the Global Reporting Initiative (GRI, 2011), which is a generic sustainability reporting framework, applicable to many sectors and organisations. For example, the indicators developed by Stamford and Azapagic (2011; 2012) are based around a core set of GRI indicators and additional indicators which are specific to nuclear power and its sustainability implications (see Chapter 3, section 3.5 for the full list). This set of indicators is aimed at a national-level assessment of energy technologies. It is angled towards nuclear power (as the project seeks to assess how sustainable nuclear power is in the UK), but it is also generic enough to be applied to renewable and fossil fuel technologies. This means that comparisons between technologies can be made, in addition to assessments of energy mixes in future energy scenarios.

This is one of the most comprehensive and integrated approaches for assessing the sustainability of energy mixes with the ability to also take into account stakeholder preferences. However, as this type of indicator set assesses sustainability of a particular energy mix at a point in time, wider sustainability issues which cannot be captured by this approach. These issues might include energy implementation issues such as government capital, carbon reduction targets, the changing nature of public opinion and future expected energy needs. These issues and their evaluation can be described as ‘problem sensitivities to wider sustainability considerations’. Even if a certain technology is deemed sustainable through the assessment of its impacts using sustainability indicators, the ‘bigger picture’ or national conditions may mean that implementation or expansion of a certain energy technology is indeed ‘unsustainable’. Such issues can be considered by the use of indicator sets that seek to assess trends and the possible effects of policy. The IAEA’s Indicators for Nuclear Power Development (INPD) are one particularly relevant set that assess the wider implications of nuclear power development or implementation (IAEA *et al.*, 2005).

Governments often need to make such evaluations for energy system planning. This is especially relevant in the case of nuclear energy expansion or implementation, which encompasses many long-term issues and often requires economic stimuli from government due to high and uncertain costs associated with nuclear power, such as waste and decommissioning. As stated previously, indicator frameworks that feed into multi-criteria decision-analysis do not take into account possible effects of actions (such as the building of new nuclear power stations) or specific country conditions, such as energy policy. The next section describes the use of one such national-level, technology-specific indicator set that allows governments to assess their own country conditions before implementing energy policy.

2.3.2 Consideration of wider sustainability issues

Despite the numerous drivers for the development or expansion of nuclear power, significant barriers to nuclear power may also exist and need to be assessed at the national-level from the perspective of government. A national-level, government perspective that considers indicator trends and the effects of certain policy decisions will allow individual countries to assess the wider drivers and barriers for nuclear power. They may therefore be used by policy-makers to assist in decision-making on this subject.

To aid this decision-making, the IAEA (IAEA *et al.*, 2005) have developed Indicators for Nuclear Power Development (INPD). The indicators take into account energy, economic, environmental, institutional and social perspectives of nuclear power implementation or expansion. The indicators are largely descriptive, with some quantitative measures. Use of the indicators is primarily aimed at developing countries or emerging economies which may currently be considering adding nuclear power into their energy mix.

The use of nuclear power is often viewed as implementable only in stable and developed countries due to the perceived threat of proliferation in more unstable, economically-developing countries. The Nuclear Non-Proliferation Treaty aims to limit this proliferation threat but also to allow countries “the right to peacefully use nuclear technology” (IAEA, 1970). The IAEA’s INPD have been developed to evaluate the readiness of a country to develop or expand nuclear power in this context. In addition to this specific use, the INPD may also be useful tool for developed countries. Through use of the INPD, analysts and policy-makers may understand their country-specific situation and trends, impacts of recent policies and potential impact of policy change. This is demonstrated in Chapter 6 by applying the IAEA’s INPD to UK conditions to highlight government-level strengths and weaknesses in managing a nuclear power programme.

2.4 Multi-Criteria Decision-Analysis

2.4.1 Introduction

This section reviews multi-criteria decision-analysis (MCDA) as a technique for exploring complex problems in the decision-making arena. An evaluation of specific methods and tools developed under this umbrella term is also made which have been or may be applied to the energy sector specifically.

2.4.2 MCDA as an approach

Multi-criteria decision-analysis (MCDA) is a well-known branch of decision-making within a class of operations research models that deal with multiple criteria (Pohekar and Ramachandran, 2004). In the multiple criteria decision analysis process, judgements are made across a range of criteria or choices in relation to a particular defined problem. In addition to the large amount of criteria that are being considered, many stakeholders are usually involved in the decision-making process, complicating the problem further. The structure of the MCDA problem promotes transparency and leaves an audit trail of decisions or choices made. This is an important factor for a MCDA approach to have; it enables decision makers to reflect on how decisions have been reached depending on the weighting or choice of criteria. In addition, exploration of alternative ‘pathways’ may be undertaken (Belton and Stewart, 2002).

The continued use and development of MCDA with regard to environmental and sustainability decision making has occurred largely due to the increasing complexity of the problems encountered. MCDA allows the multiple and conflicting criteria to be presented, considered, balanced and synthesised in a transparent and explicit way. It should be noted that the use of MCDA approaches in the decision-making context will not give the ‘right’ answer, or eliminate subjectivity inherent in all decision-makers and stakeholders (Belton and Stewart, 2002). However, its use should be based on the integration of objective measurement and explicitly highlight any subjectivity in the process (Belton and Stewart, 2002).

MCDA can be further split into two specific categories of decision making class: programming methods, which includes optimisation and ‘satisficing’ approaches and; multi-attribute decision analysis (MADA) which includes elementary, value-based and outranking approaches (Azapagic and Perdan, 2005b).

In the next section, specific descriptions of MCDA methods and tools are given, based on the classification of the approaches into two distinct sets: the programming methods and the MADA techniques.

2.4.3 MCDA methods and tools

2.4.3.1 Programming methods

2.4.3.1.1 Optimisation approach: multiple objective optimisation (MOO)

These methods are part of the Pareto set of methods (Coello Coello et al., 2006), which are based on a mathematical model formulation of the decision problem being investigated. The model may then be optimised by maximisation or minimisation of the decision criteria. Maximisation or minimisation of the decision criteria are subject to equality and inequality constraints which describe vectors of continuous and discrete decision variables. These models can be formulated as Linear Programming (LP), Non-linear Programming (NLP), Mixed Integer Linear Programming (MILP) or Mixed Integer Non-linear Programming (MINLP) (Azapagic and Perdan, 2005b). The optimisation process leads to a range of solutions which are nondominated or noninferior, meaning that no alternative is better than any other on all criteria (Azapagic and Perdan, 2005b; Coello Coello et al., 2006).

Weights may or may not be applied to criteria in the multi objective problem. If preferences are elicited, the weights may then be aggregated and the problem is therefore reduced to a single objective optimisation (SOO) problem (Azapagic and Perdan, 2005b). This will generate a single solution and although it may be optimal in the Pareto sense, it may not be acceptable to all stakeholders (Azapagic and Perdan, 2005b). When weights are not applied prior to the optimisation process, a range of alternatives may then be evaluated by decision-makers and/or stakeholders.

Although MOO techniques are very useful in the public policy and corporate decision-making arenas, specialist mathematical modelling software and skills are needed in order to carry out an optimisation approach. In addition, because MOO generates many decision alternatives, it can be difficult to make the necessary trade-offs in order to reach a solution (Azapagic and Perdan, 2005b). Because of this, Azapagic and Perdan 2005b suggest that a MOO technique may act as a screening tool before a multi-attribute decision analysis (MADA) method is applied to elicit and aggregate preferences.

2.4.3.2 ‘Satisficing’ approaches

The ‘satisficing’ approaches in preference modelling aim to satisfy stakeholders’ preferences rather than optimise them in MOO. An ‘ideal’ situation is sought and then a range in ‘distance’ from the solution that is acceptable is defined. Mathematical methods such as goal programming (GP) will find the most feasible solution closest to the ideal (Azapagic and Perdan, 2005b).

The stakeholders or decision-makers set goals for each criterion that they want to achieve. The most suitable option will then be defined as the one where there is least deviation from the goal for each criterion. An iterative approach is needed when implementing this method in preference modelling as it is hard to define preferred goals before modelling the solution.

There are many varieties of the GP method due to its on-going evolution since the earliest attempts in the 1960s (Belton and Stewart, 2002). Some modifications allow weights for each criterion to be defined, so that their importance throughout the modelling process is readily observable and their deviation from the goal easily definable (Azapagic and Perdan, 2005b). Because of the potential 'shift' in goal from the ideal, sensitivity analyses should be conducted in order to determine the change in the decision parameters (Azapagic and Perdan, 2005b). Due to the iterative nature of the GP method and the associated tools, it can be difficult for those unfamiliar with the decision-making process to implement seamlessly.

2.4.3.3 MADA techniques

MADA (multi-attribute decision-analysis) techniques are classified into the following groups: elementary methods; value- and utility-based methods; and; outranking methods (Azapagic and Perdan, 2005b).

2.4.3.3.1 Elementary methods

Elementary methods do not require quantification of weights or preferences, which is needed in the other MADA methods.

Conjunctive and disjunctive methods: Unacceptable alternatives are taken out through use of criteria thresholds. In conjunctive models, levels of performance for criteria are defined and those which do not meet that level are eliminated. The disjunctive model allows alternatives to 'pass' if it exceeds the threshold in one or more criteria. These methods can be used as filters in order to determine the only acceptable alternatives amongst the decision-makers criteria preferences.

Lexicographic method: Criteria are ranked in order of importance of decision makers' values and the solution or alternative that performs the best on the most highly valued criterion is the most acceptable. This means that effectively, an alternative is chosen based on its performance on only one criterion.

Maximin and maximax methods: In the maximin method, alternative options are scored by ranking their performances on the criteria they perform worst on. In the maximax method, alternatives are scored based on which criteria they perform best.

2.4.3.3.2 Value- and utility-based methods

These methods require decision makers to define values or 'utilities' for decision criteria and they include Multi-Attribute Value Theory (MAVT), Multi-Attribute Utility theory (MAUT) and Analytical Hierarchy Process (AHP).

Multi-Attribute Value Theory (MAVT): MAVT is used in decision-making where the outcomes of alternatives are known by the decision-makers. Real numbers are associated with each alternative, so that preferences may be ranked consistently with decision-makers' values (Belton and Stewart, 2002). MAVT involves the following three steps:

i) Intra-criteria comparison or assignment of value scores;
ii) Inter-criteria comparison or assignment of weights to decision-criteria; and
iii) Aggregation of scores and weights to guide decision-makers in choosing the preferred alternative.

i) Intra-criteria comparison or assignment of value scores*:* Values of the performance of alternatives with respect to the decision criteria are displayed in a performance matrix. The scores are displayed on a preference scale which will show the strength of the preferences.

ii) Inter-criteria comparison or assignment of weights to decision-criteria: At this stage, the relative performance of each criterion is determined through use of numerical weights, assigned by the decision-makers. The criteria are first ranked in order of importance. The criterion which displays the greatest 'swing' in importance has the greatest overall value and is considered the most important. Numerical weights are then assigned to each criterion in order to display the amount of 'swing' for each. In order to do this, decision-makers are asked to assess the value of the second-highest ranked criterion in comparison the highest ranked criterion. The highest ranked criterion is usually given the value of 1 or 100, and all other criteria measured in relation to their worth compared to the most highly ranked criterion (examples of this method of preference elicitation include the SWING and the SMART methods).

iii) Aggregation of scores and weights to guide decision-makers in choosing the preferred alternative: Aggregation of the weights is then carried out in order to determine the best alternative. There are two methods by which to do this: criteria weights may be aggregated across each alternative or aggregation can take place amongst sets of criteria that have the same parent criterion. The aggregated weight sets will then also be aggregated until an overall score is reached. The highest scoring alternative is the most desirable.

Multi-Attribute Utility theory (MAUT): MAUT is especially applicable in decision-making situations where uncertainty needs to be taken into account. It is related to MAVT, but uses the techniques of MAVT to deal with uncertainty in certain decision problems (Belton and Stewart, 2002). MAUT allows the probability of anticipated consequences to be calculated by computing its 'expected utility'. The alternatives can then be ranked according to the sums of their utility scores. The highest utility score will be the preferred option for decision-makers. MAUT models can prove to be very complicated. However, more simple MAUT models can be used in cases where complex modelling is not needed.

Analytical Hierarchy Process (AHP): The AHP approach uses pairwise comparisons of criteria in order for weights and scores to be determined. Decision-makers define the relative performance of one criterion in relation to another and also for alternatives. Scores for alternatives may be determined by evaluation of their performance on each criterion. The weights for the compared criteria are assigned based on a 9-point ratio. This means that a score of 1 is given if criteria are deemed equal in value, 3 if one is moderately more important than the other and 9 if one of the criteria is substantially more important than the other.

2.4.3.3.3 Outranking approaches

These approaches are similar to AHP in that they use pairwise comparisons in order to eliminate options which are dominated by others (for example, if one criterion outperforms another, it will not be considered). This means that values are not defined for criteria or alternatives, but some criteria may be 'outranked'. The main difference between these approaches and value function approaches is that outranking methods do not aggregate values (Belton and Stewart, 2002). There are many outranking methods currently used which include: the ELECTRE family; PROMETHEE; MELCHIOR, ORESTE and; REGIME.

After determination of which alternative outranks another, the assessments then need to be combined for an overall best alternative to be identified. To do this, the concordance principle, or the discordance principle may be used. When the concordance principle is used, one alternative will outrank another if it is as good as, or better than the other based on a large weight of criteria. The discordance principle states that an alternative will outrank another if it is strongly preferred.

2.4.4 Choice of MCDA method

The choice of an MCDA method for sustainability assessment will depend on many factors, for example, the number and type of decision criteria, the number of alternatives and the way in which preferences are ordered. Depending on the evolution of the project and the amount and nature of data being used, it is likely that different methods will be used at different stages of the project. Certain methods may also be used in conjunction with one another. In addition to this, the availability of decision-support software will also play an important role in the choice of MCDA method.

The above considerations have been taken into account when choosing the appropriate methods for the research carried out here. This is discussed later in the dissertation.

2.5 Stakeholder Participation in the Decision Making Process

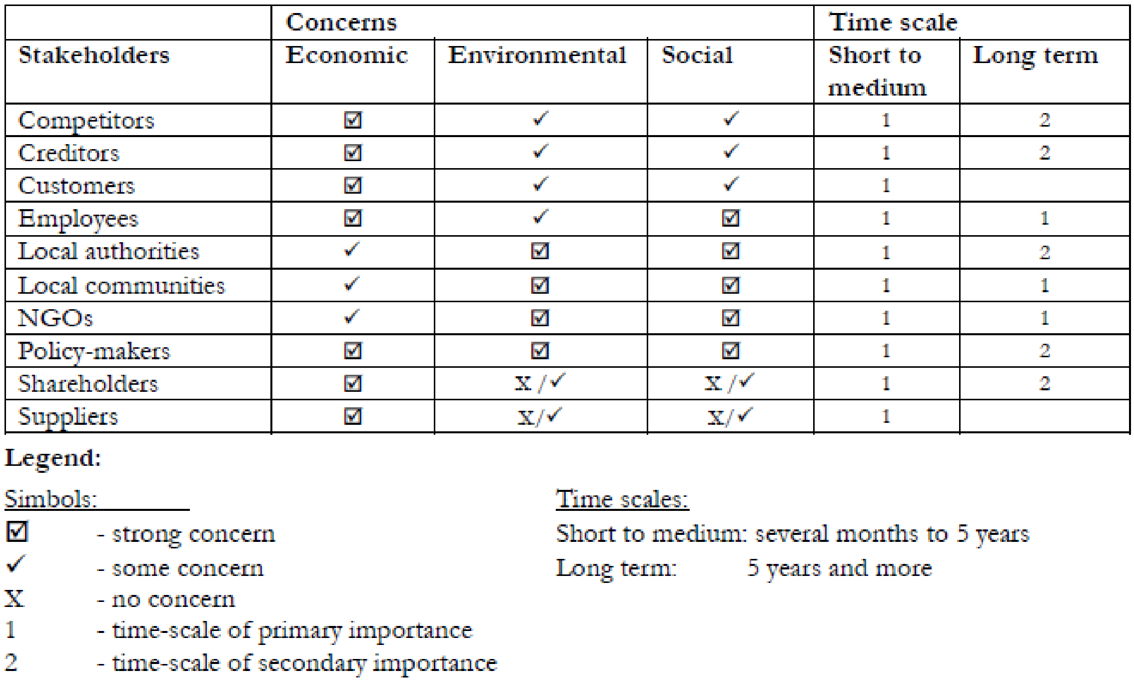
Stakeholders may be categorised into one of two, and sometimes both of the following groups: stakeholders who provide advice during the decision making process and stakeholders who may be affected by a decision that is made. The former are usually identified as experts, who provide detail on and insights into the implications of decisions and also the way in which the decision problem is framed and structured. The latter can be anyone affected by the decision being made, including the public.

To ensure that decisions made are appropriate, stakeholder involvement in the decision-making process should be an integral aspect of a decision-support framework. Although stakeholders may or may not be the decision makers, their differing perspectives on the decision problem provide diverse views about how the problem should be approached, which issues are the most important in structuring the problem and how the findings from the problem analysis should be interpreted by the decision analysts. As an example,

Table 2.1 shows a generic list of sustainability issues that may be important to different groups of stakeholders and the time scale over which they might be concerned about these issues (Azapagic and Perdan, 2003).

In the nuclear arena, decision-making and the involvement of stakeholders and the public has the potential to become very complicated due to the amount of interested parties and controversial issues that need to be assessed (for example, waste and decommissioning). It is important for decision analysts to systematically identify stakeholders’ issues, concerns and views regarding the decision problem. Public stakeholder surveys may further identify issues that expert stakeholders might not have identified and also highlight difficulties government may face in implementing a particular energy policy from particular communities or groups.

Table 2.1 A list of example stakeholder groups, their potential sustainability concerns and the related timescales (Azapagic and Perdan, 2003).



	Concerns			Time scale	
Stakeholders	Economic	Environmental	Social	Short to medium	Long term
Competitors	☑	✓	✓	1	2
Creditors	☑	✓	✓	1	2
Customers	☑	✓	✓	1	
Employees	☑	✓	☑	1	1
Local authorities	✓	☑	☑	1	2
Local communities	✓	☑	☑	1	1
NGOs	✓	☑	☑	1	1
Policy-makers	☑	☑	☑	1	2
Shareholders	☑	X /✓	X /✓	1	2
Suppliers	☑	X/✓	X/✓	1	

Legend:

Simbols:
☑ - strong concern
✓ - some concern
X - no concern
1 - time-scale of primary importance
2 - time-scale of secondary importance

Time scales:
Short to medium: several months to 5 years
Long term: 5 years and more

Public participation in the decision-making process also increases understanding amongst the public of the main issues with the implementation of nuclear power. The way the decision is made can be seen, therefore the more transparent the framework, the better. Increased transparency builds trust between analysts and stakeholders. Individuals may not agree with the decision, but they can see on which attributes the decision has been made.

The approach to stakeholder participation in decision-making may also be viewed as either a 'top-down' or bottom-up' approach (Fraser *et al.*, 2006). The bottom-up approach uses stakeholders to construct the problem with issues, indicators and objectives. In addition, preferences from the public may be analysed to reveal any disparity in preferences between stakeholder groups. Top-down approaches may seek to achieve group consensus on a decision-problem through deliberation of the issues with stakeholders at the same time. These approaches are defined as prescriptive and descriptive decision theory approaches. A prescriptive approach is one which guides stakeholders through the decision problem and aims to educate stakeholders about the main issues associated with the problem being analysed. Conversely, descriptive decision theory describes how stakeholders make decisions without guidance. Normative theory describes how decision should be made by a rational person, taking into account the relevant issues. Once a framework has been built and the decision-support framework has taken into account all perspectives and view, the decision model is described as 'requisite' (Phillips, 1984).

2.5.1 Nuclear-specific stakeholder engagement

In the nuclear arena, decision-making and the involvement of stakeholders and the public has the potential to become very complicated due to the number of interested parties and controversial issues that need to be assessed (for example, waste and decommissioning). Thus, it is important for decision analysts to systematically identify stakeholders' issues, concerns and views regarding the decision problem. Public stakeholder surveys may further identify issues that expert stakeholders might not have identified and also highlight difficulties government may face in implementing a particular energy policy from particular communities or groups.

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The position of an organisation will also affect its success in delivering a successful public engagement campaign. For example, BNFL (BNFL, 2004) and CoRWM's (CoRWM

2006; 2009a, b, c) stakeholder participation processes were immediately opposed by some groups and individuals, who viewed such organisations as pro-nuclear and therefore that the decision has already been made that nuclear power is a viable electricity generating technology. The public and other organisations are more likely to engage in the consultation process if they believe that the body is approaching the problem from an unbiased viewpoint. Therefore they will want to want to engage with the project in order to assert their influence over the problem and how the decision is made.

An increasing number of sustainability assessments have included stakeholder engagement in their frameworks, especially with regard to public consultation in science and environmental decisions. This move began with European guidelines from the Aarhus Convention, which took place in June 1998 and forged a new process for 'public participation in the negotiation and implementation of international agreements' (UNECE, 1998 June). The UK Government also laid the case for public consultation in various branches of decision-making relating to decisions regarding science and technology in its Select Committee on Science and Technology Third Report (House of Lords, 2000).

In the following two sections (2.5.1 and 2.5.2), some examples of stakeholder engagement are discussed.

2.5.1 Examples from research projects

Over the last ten years, there have been numerous research papers that have incorporated a stakeholder participatory approach into their decision-support frameworks (van den Hove, 2000; Alberts, 2007; Cuppen *et al.*, 2010 Komendantove *et al.*, 2012). Earlier papers focus on the relevance of a participatory stakeholder approach in the environmental arena (such as van den Hove, 2000), and some later papers address the issue of the type and range of stakeholders that should be consulted in decision making on energy policy (see Alberts, 2007). More recently, publications regarding energy policy describe methodologies for integrating stakeholder views (Cuppen *et al.*, 2010) and also the public perception of various energy technologies (Komendantove *et al.*, 2012; Tokushige *et al.*, 2007; Graham *et al.*, 2009). Surveying the public's perception of energy technologies allows identification of barriers to implementation of the technologies. Through identification of the risks, strategies can then be developed which implement these technologies in a way that would be the most publicly acceptable. More recently, defining ways to include the diversity of stakeholder opinion and the amount of information produced from stakeholder dialogue have been suggested (Cuppen *et al.*, 2010).

The Artemis project used stakeholders as a means of addressing uncertainty in sustainable energy policy (Madlener and Stagl, 2005) and to understand stakeholder perspectives of the Artemis renewable energy scenarios (Madlener *et al.,* 2007). The Artemis project researchers argue that a participatory process in energy evaluation allows: differentiation of the level of promotion of the technologies according to their socio-ecological economic impact; explicit accountability for stakeholder preferences (Madlener and Stagl, 2005); and stakeholder support for national energy policy discourse through involvement (Madlener *et al.,* 2007). The Artemis approach includes multi-criteria evaluation of stakeholder preferences and discussions (interviews) and workshops to quantify stakeholder values and develop the criteria and scenarios under which the energy technologies would be assessed.

The ExternE project does not explicitly include a participatory process in its methodology. However, the NEEDS project, which is a follow-on project of ExternE includes a substantial aspect of stakeholder engagement in the decision-support framework. The aims of NEEDS are extended from ExternE to include a long-term perspective of energy sustainability, therefore considering policy and using multi-criteria decision-analysis (MCDA) as part of its methodology to assess the implementablility of energy technologies. The NEEDS methodology included the mapping of stakeholder preferences onto electricity options and mixes using multi-criteria decision-analysis and also stakeholder surveys to obtain feedback on the proposed criteria and indicators and to elicit the stakeholder preferences. The intended outcome of this approach was to enable exploration of stakeholder preferences and allow for a more robust framework by taking on suggested improvements to the methodology by stakeholders. In addition, the project includes methods to disseminate and communicate the project with a rationale of this aiding the project's development and also being externally transparent to stakeholders.

2.5.2 Examples from UK government consultations

In addition to the energy assessment frameworks discussed in the previous section, two significant stakeholder engagement projects with a nuclear focus have been implemented by the UK Government over the last 10 years. These are the BNFL National Stakeholder Dialogue (BNFL, 2004) and the Committee on Radioactive Waste Management's various stakeholder consultations (CoRWM, 2006, 2009a, b, c).

British Nuclear Fuel Ltd. (BNFL) National Stakeholder Dialogue was the longest, most wide ranging and thorough process of its kind undertaken in Europe in the nuclear sector conducted between 1998-2004. The Dialogue involved a wide range of organisations and individuals that were interested in or concerned about nuclear issues. Its aim was to: "*inform BNFL's decision-making process about the improvement of their environmental performance in the context of their overall development*" (BNFL, 2004). The outcome of the dialogue was reported in 14 final reports. Some reported the findings of working groups such as the Spent Fuel Management Options Working Group; Waste Working Group; Discharges Working Group; Plutonium Working Group; Business Futures Working Group; and Security Working Group. Other reports detailed the findings from fact-finding studies such as a "Socio-Economic study of West Cumbria" and "Diversification Opportunities at BNFL". Many of the 'working group' reports detailed feedback from stakeholders on specific issues, but did not aim to quantify these issues. Only the 'Spent Fuel Management Options Working Group' used a quantitative methodology (multi attribute decision analysis) to map stakeholder values onto to options for spent fuel management in the UK.

The Committee on Radioactive Waste management (CoRWM) is an independent body set up by Government in 2003 to assess the options for disposal of radioactive waste in the UK. CoRWM communicates their findings to Government and the public. The methods by which the Government intended to deal with radioactive waste were communicated by CoRWM, to the public via the consultation process. Their work covered consultation on research and development on radioactive waste methods, geological disposal of high-level waste and the interim storage of waste as well as stakeholder workshops covering the same themes (CoRWM, 2006, 2009a, b, c). The main objective of involving stakeholders in these processes was to find a solution for radioactive waste management and disposal that is the 'most acceptable' to all stakeholders.

However, the consultation process failed and did not identify either the waste management method to be used or a repository where the waste would be stored. Furthermore, this consultation process is now outdated. Given the changes in the nuclear debate since, it is important that a stakeholder consultation be carried out again, but this time looking not only at the waste management but also at new nuclear build, taking into account a range of environmental, economic and social sustainability issues. This is particularly relevant following the Fukushima accident in 2011.

2.5.3 Summary

Assessing sustainability of nuclear power in the present and for the future is a complex, multi-criteria problem that requires simultaneous consideration of a number of techno-economic, environmental and social aspects, in addition to the consideration of stakeholder perspectives and wider sustainability issues, such as national level drivers and barriers. To date, there have been few attempts to develop an appropriate decision-support framework to aid decision-makers and stakeholders assess the sustainability of nuclear power.

Public engagement and stakeholder involvement programmes are implemented to engage people in a decision making process that they have an interest in, or that may affect them. They may be experts, representatives of different interest groups, or the general public. Energy and environmental decision making, in particular, has shifted from much less democratic strategies, where the public were informed of a decision by elected representatives who made the decision, to more direct democracy of public participation that seek to include their values and beliefs into the equation. The UK has been relatively slow on the uptake of public participation processes although, steady progress is being made. However, there is still scepticism about public engagement carried out by the Government.

Most energy and environmental decisions are extremely complex and require thorough analysis of the negative and positive impacts of any small and large decisions. Involving the public gives decision makers a clear idea of what the public want rather than making assumptions about what they think they want. Involving local people in local decisions also provides information that may have otherwise been overlooked. By these means, the decision making process is strengthened and the quality of the decision is improved.

Participation of different groups with opposing views also helps to resolve conflict. Compromise may be reached with negotiation and, when different viewpoints and values are heard, participants may become more sympathetic to the opposing cause. By opening up the decision making process to the public, granting them some control over their own environment, and so increasing transparency, trust can be built. Participatory processes also seek to educate and inform the public in matters of which they may otherwise have been fearful.

The multi-criteria decision-support framework used in this work integrates quantitative and qualitative indicators, allowing stakeholders to elucidate their preferences and trade-off different sustainability criteria. The use of a multi-criteria decision-support framework enables the assessment of sustainability of nuclear power in the UK electricity mix specifically, but is also generic enough to be applicable to other energy options. Comparisons of different energy options with nuclear can be carried out by decision-makers within the framework using a number of relevant sustainability criteria. Therefore, a number of potential future energy scenarios are also developed (Section 3.4), which identifies of the most sustainable electricity mixes and their sustainability impacts and issues.

The decision-support framework applied within this thesis and presented in the next chapter aims to integrate stakeholder preferences and values throughout the decision-making process.

3 Methodological Approach

3.1 Introduction

This section outlines the methodology applied in this work for an integrated sustainability assessment of nuclear power, relative to other energy technologies. The main focus is on the application of the multi-criteria decision-support framework developed within the SPRIng project (Azapagic *et al.*, 2011). The various aspects of the framework and areas of work that have been undertaken in order to make rigorous, robust and transparent assessments are discussed in section 3.2.

Section 3.3 describes the stakeholder engagement and consultation methodology that has been used to communicate results to, and receive feedback from a divergent group of nuclear- and energy-specific stakeholders. Section 3.4 outlines the use of future energy scenarios in which the sustainability of nuclear power has been assessed. Section 3.5 describes how the decision problem (assessing the sustainability of nuclear power against other UK electricity options) is addressed through the use of sustainability indicators developed within the SPRIng project by Stamford and Azapagic (2011). Finally, section 3.6 describes the specific MCDA methods used.

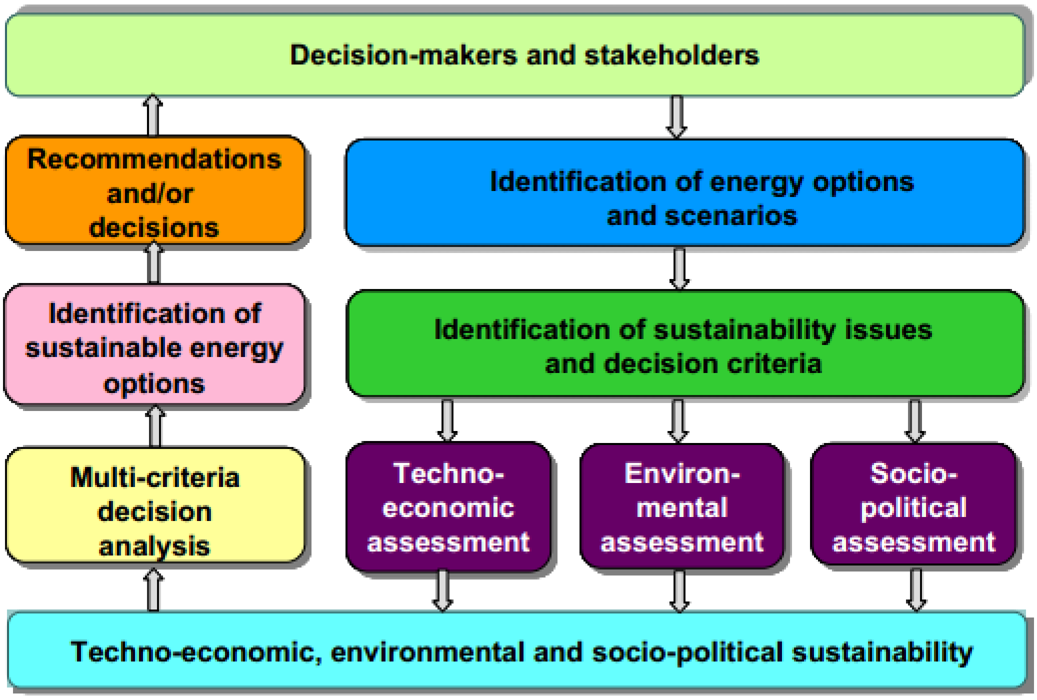


Figure 3.1 The SPRIng decision-support framework (Azapagic *et al.*, 2011).

3.2 The Decision-Support Framework

The decision-support framework applied in this work is outlined in Figure 3.1. The approach is based on the work by Azapagic and Perdan (2005a&b), but has been adapted for the sustainability assessment of nuclear power generation in the UK. This framework follows a systems approach, whereby all aspects of the decision problem (for example, a range of energy options or future energy scenarios) are considered systematically and holistically and take account of the whole life cycle of the decision alternatives being under review (Azapagic and Perdan, 2005a). This is especially appropriate for decision problems regarding energy alternatives, in which there are many competing energy options, stakeholders and decision criteria. Specific areas of the decision-support framework that have been developed as part of this thesis include: stakeholder engagement and communication; the development of future electricity scenarios for the UK; the application of two alternative indicator frameworks to assess the decision problem being evaluated in this work; and multi-criteria decision modelling of the alternatives being evaluated.

In section 3.3, the methodology used in order to identify expert and public stakeholder opinion on electricity options and the importance of sustainability indicators and aspects is outlined. Stakeholders are integral to the decision-support framework both in terms of their valuable input in framing the decision problem and in order to model stakeholder preferences through the use of multi-criteria decision-analysis. This helps explore the impact of stakeholder opinion on a variety of future energy scenarios or choice between competing energy options. The development and use of four future energy scenarios specific to the UK as part of the decision-support framework is outlined in section 3.4. Identification of energy options and energy scenarios to be evaluated within the decision-support framework enables the aim, scope and boundaries of the study to be determined, within which data is collected in order to quantify and qualify the problem being analysed.

Section 3.5 then details the indicator framework (Stamford and Azapagic, 2011) applied in this work in order to determine the techno-economic, environmental and social impacts of competing energy technologies and future energy scenarios. Finally, section 3.6 describes the specific multi-criteria decision-analysis methods used in order to carry out preference modelling of stakeholder values within the decision-support framework.

3.3 Stakeholder Engagement and Consultation

The decision-support framework starts with identification of stakeholders involved in the nuclear arena. Stakeholder engagement and consultation are a vital aspect of any decision-support framework. The method by which stakeholder views are integrated into the framework and outputs of the sustainability modelling are fed back to stakeholders is displayed in Figure 3.1. This shows how stakeholder views and priorities are initially taken into account through the development of the framework of indicators to define the decision problem and identify the sustainability indicators (see sections 3.5). Subsequent environmental, techno-economic and social modelling of the sustainability indicators leads to outputs which may then be weighted by stakeholder preferences by the use of multi-criteria decision-analysis (see section 3.6). The effect of stakeholder preferences on the sustainability of nuclear and other electricity technologies is then presented back to stakeholders in order to display how individual perspectives affect decision-outcomes.

This method of stakeholder engagement and communication helps maintain transparency of the decision-support framework, which is one of the main objectives to be met through the development of the decision-support methodology. Therefore, it is necessary to communicate all assessment results back to stakeholders in order to enable understanding of others' perspectives, engage them in the decision-making process and integrate new knowledge through understanding of the main issues.

Identification of stakeholders has been carried out through a combination of extensive literature searches, direct contacts with different groups of interested parties and advertisement of the second-stage expert questionnaire through use of a variety of websites and newsletters (see section 4.2.2). The key stakeholders include the nuclear and other energy industry, Government, investors, NGOs, local authorities, local communities and the general public. In total, 32 representatives from these groups of expert stakeholders have been consulted as part of the first-stage consultation work as follows (listed in alphabetical order):

- Aker Solutions
- AMEC
- Centre for Ecology and Hydrology (CEH)

- Combined Heat and Power Association (CHPA)
- Costain
- Department of Energy and Climate Change (DECC)
- EDF Energy
- Environment Agency (EA)
- European Commission (EC)
- Friends of the Earth (FoE)
- Health and Safety Executive (HSE)
- Horizon – E.ON/RWE nuclear joint venture
- National Grid
- National Nuclear Laboratory (NNL)
- Organisation for Economic Cooperation and Development (OECD)
- Serco
- Society for the Environment (SocEnv)
- Southern Solar
- SPRIng project researchers
- Sustainable Industrial Systems research group (SIS)
- University of Central Lancashire (UCLan)
- University of Leeds – Health Economics
- University of Manchester (UoM)
- Westinghouse

In addition, 45 expert stakeholders were consulted as part of the expert MCDA consultation process, some of which also took part in the first stage consultation exercise (see section 4.2) and over 600 members of the general public have also been consulted on the sustainability issues related to energy and specifically nuclear power. The results of this work are presented in Chapters 4 (expert stakeholder engagement) and 5 (public engagement).

3.4 Future Electricity Scenarios

The next step in the decision-support framework is definition of future energy options and scenarios for the UK. Four divergent scenarios have been defined within the SPRIng project that have been used in this work; they are termed A, B, C and D scenarios. They describe the world in 2020, 2035, 2050 and 2070 in terms of: international political context; UK governance; the economy; public attitudes to nuclear power; climatic factors and; security of fuel supply. The scenarios are based on the extent to which the UK meets its carbon emissions reductions targets (which are currently set at 80% of 1990 levels by 2050). Existing decarbonisation scenario work developed by the Tyndall Centre (Anderson *et al*., 2008; Mander *et al*., 2008) and UKERC (2009) have also been used in the nuclear scenario development. The three main themes of the scenarios are described below:

Scenario A – carbon targets abandoned/failure to meet targets

- International relations decline slightly
- Frequent changes of UK Government
- Emphasis on economic growth due to low levels of growth in the recent past
- Public prioritise the economy over the environment
- Increasing emphasis on security of supply
- Global emissions follow those of the UK. The UK must therefore adapt to/cope with future climate changes

Scenarios B and C – emissions broadly in line with UK targets and UK Climate Change Committee emissions reductions

- Strong international agreement is reached on climate change
- Political parties co-operate - policies are more interventionist
- Growth in ‘green’ technologies and private investment in sustainability
- Willingness to make personal behavioural / lifestyle changes
- Non-CO_2, greenhouse gas emissions deliver a 70% reduction. International aviation and shipping play their full part. UK emissions peak between 2012-2014 and reduce by 6-9% pa
- European grid established - less reliance on indigenous fossil fuels. Non-fossil fuel energy exploited domestically

Scenario D – carbon emissions reduced by 100% of 1990 levels

- Strong international agreement reached on climate change. Enforcement taken seriously - responsibility shared equitably
- More centralised and interventionist government - less emphasis on sovereignty.
- Move from a rights-based to a utilitarian society
- Public are supportive of initiatives to reduce greenhouse gas emissions
- UK emissions peak between 2012-2014 and reduce by 6-9% per annum thereafter Energy sector compensates for the stabilisation of international shipping, aviation and non-CO_2 emissions from agriculture
- Exploitation of non-fossil fuel energy and successful implementation of carbon capture and storage.

The four scenarios were initially been defined from a ‘top-level’ perspective and are descriptive in nature. Further work on the scenarios has focused on defining the electricity penetration and nuclear penetration in each case. As the project has been carried out iteratively, more specific scenarios have been generated as part of this PhD work to define the UK’s electricity mix in more detail (see Chapter 8). The scenarios are each compared to the UK’s base case scenario (using data from the year 2008). Emerging nuclear technologies such as Gen III+ and Gen IV as well as carbon capture and storage are also considered as part of the future electricity mix in the UK (see Chapter 7).

3.5 Sustainability Assessment

The many stakeholders involved in the nuclear energy problem means that the sustainability issues and criteria are numerous and often conflicting. Twenty-two sustainability issues have been identified in collaboration with the stakeholders and have been translated into 43 indicators (for details, see Stamford and Azapagic, 2011). These indicators have been used in this work to assess the sustainability of different electricity options and future electricity scenarios. All indicators presented in this framework have been measured and quantified on a life cycle basis. As shown in Tables 3.1-3.3, the indicators are categorised into techno-economic, environmental and social aspects of sustainability.

Techno-economic indicators (Table 3.1) are important sustainability measures to consider as they define how feasible a technology is economically, i.e. whether it can compete commercially with other electricity-generating technologies. The technical indicators also demonstrate whether the technology is technically feasible, e.g. whether it can compete in terms of electricity produced, be operational for generations into the future (depending on the lifetime of fuel reserves) or produce electricity relatively quickly (total construction time from planning consent). In this category, there are four economic issues expressed by seven economic indicators, including levelised cost of generation, financial incentives, cost variability and economic operability. There are also six technical indicators that cover three technical issues: technical operability, technological lock-in and immediacy.

Table 3.1. Techno-economic indicators and their units of measurement.

Category	Sustainable Development Issue Addressed	Indicator	Unit
Techno-economic	Operability	Capaciyt factor (power output as a percentage of the maximum possible output)	Percentage (%)
		Availability factor (percentage of time plant is available to produce electricity)	Percentage (%)
		Technocal dispatchability (ramp-up rate, ramp-down rate, minimum up time, minimum down time)	Summe rank
		Economic dispatchability (ratio of capital cost to total levelised cost)	Dimensionless
		Lifetime of global fuel reserves	Years
	Technological lock-in	Ratio of plant flexibility (ability to provide tri-generation, negative GWP and/or thermal/thermochemical H_2)	Years-1
	Immediacy	Time to plant start-up from start of construction	Years
	Levelised cost of generation	Capital costs	Pence/kWh
		Operation and maintenance costs	Pence/kWh
		Fuel costs	Pence/kWh
		Total levelised costs	Pence/kWh
	Cost variability	Fuel price sensitivity (ratio of fuel cost to total levelised cost)	Dimensionless
	Financial incentives	Financial incentives and assistance (e.g. ROCs, taxpayer burdens)	Pence/kWh

The environmental indicators (Table 3.2) have been selected to capture the environmental impacts of energy technologies (with a specific focus on nuclear power) on natural systems, including the atmosphere, aquatic bodies and land. These indicators (as with the economic, social and technical indicators) are applicable at the local, regional and national level. The environmental indicators are grouped into eight categories, each dealing with different environmental impact issues; from the material recyclability, to land use and quality.

Life Cycle Assessment (LCA) has been used as a tool to quantify the environmental impacts of each energy technology along the whole life cycle. The environmental impacts considered using the LCA tool include: global warming, ozone layer depletion, acidification, eutrophication, photochemical smog and eco-toxicity and are detailed in Table 3.2. The life cycle impacts for the indicators detailed above have been quantified using the CML 2001 impact assessment method (Guinee *et al.*, 2001).

Table 3.2. Environmental indicators and their units of measurement.
[a] DCB – dichlorobenzene

Category	Sustainable Development Issue Addressed	Indicator	Unit
Environmental	Material recyclability	Recyclability of input materials	Percentage (%)
	Water eco-toxicity	Freshwater eco-toxicity potential	kg 1, 4-DCB[a] equiv./kWh
		Marine eco-toxicity potential	kg 1, 4-DCB[a] equiv./kWh
	Global warming	Global warming potential	kg CO_2 equiv./kWh
	Ozone layer depletion	Ozone depletion potential (CFC and halogenated HC emissions)	kg CFC-11 equiv./kWh
	Acidification	Acidification potential (SO2, NO_2, HCl, NH_3 emissions)	kg SO_2 equiv./kWh
	Eutrophication	Eutrophication potential (N, NOx, NH_4^+, PO_4^{3-} etc.)	kg PO_4^{3-} equiv./kWh
	Photochemical smog	Photochemical smog creation potential (VOCs and NO_x)	kg C_2H_4 equiv./kWh
	Land use and quality	Land occupation (area occupied over time)	m^2yr/kWh
		Greenfield land use (proportion of new development on previously undeveloped land)	Percentage (%)
		Terrestrial eco-toxicity potential	kg 1, 4-DCB[a] equiv./kWh

Table 3.3 lists the social indicators that have been used in this work. There are 19 indicators in total which fall into eight categories, including human health impacts, nuclear proliferation and energy security.

Table 3.3. Social indicators and their units of measurement.
[a] DCB – dichlorobenzene
[b] DALY – disability-adjusted life years

Category	Sustainable Development Issue Addressed	Indicator	Unit
Social	Provision of employment	Direct employment	Person-yrs/GWh
		Total employment (direct + indirect)	Person-yrs/GWh
	Human health impacts	Worker fatalities	No. of fatalities/GWh
		Human toxicity potential (excluding radiation)	kg 1, 4-DCB[a] equiv./kWh
		Worker human health impacts from radiation	DALY[b]/GWh
		Total human health impacts from radiation (workers and population)	DALY[b]/GWh
	Large accident risks	Fatalities due to large accidents	No. fatalities/GWh
	Local community impacts	Proportion of staff hired from local community relative to total diret employment	Percentage (%)
		Spending on local suppliers relative to toal annual spending	Percentage (%)
		Direct investment in local community as a proportion of total annual profits	Percentage (%)
	Human rights and corruption	Involveement of countries in the life cycle with known corruption problems (based on Transparency International Corruption Perceptions Index)	Score (0-10)
	Energy security	Amount of fossil fuel potentiall avoided	toe/kWh
		Diversity of fuel supply mix	Score (0-10)
		Fuel storage capabilities (energy density)	GJ/m^3
	Nuclear proliferation	Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	Score (0-3)
	Intergenerational equity	Use of abiotic resources (elements)	Kg Sb equiv./kWh
		Use of abiotic resources (fossil fuels)	MJ/kWh
		Volume of radioactive waste to be stored	m^3/kWh
		Volume of liquid CO2 to be stored	m^3/kWh

3.6 Multi-Criteria Decision-Analysis

As discussed and summarised in section 2.4, there is a choice of many MCDA methods to choose from when evaluating the impacts of a range of energy or future scenario options, based on a number of conflicting criteria, or indicators. In this work, MCDA has been used in order to model expert stakeholder, public opinion, and also to provide equal (unbiased) weighting on the indicators in order to compare how differing perspectives may affect the choice of energy option or scenario. In the case studies which used stakeholder weights in the evaluation of the future energy scenarios (see chapter 8), a decision hierarchy tree using the Web-HIPRE software (Mustajoki and Hamalainen, 2000) was produced. Within the decision tree, the bottom-level indicators and top-level sustainability aspect categories into which the indicators fall (i.e. techno-economic, environmental and social) were weighted within the same decision model. In addition, decision models using stakeholder preferences for the competing electricity technologies in order to rank the future energy scenarios were also developed. Web-HIPRE has been used extensively with regard to emergency nuclear accident management (see Bartzis, *et al.*, 2000), however, this kind of nuclear appraisal is outside the scope of this thesis and therefore has not been considered as part of this work.

The generic steps undertaken when out multi-criteria decision modelling within this thesis included:

- selection of the criteria or indicators which are to be scored and weighted in order to evaluate the competing energy or scenario options;
- scoring of each alternative (which may be an energy option or future energy scenario in the case of this work) on the basis of each alternative's performance under each sustainability indicator using the multi-attribute value theory method (MAVT was used in all cases within the cases studies carried out within this thesis); and
- weighting of the sustainability indicators and sustainability aspects (either equal weighting or through use of stakeholder weights) using the decision tree model provided within the Web-HIPRE software (Mustajoki and Hamalainen, 2000).

The stakeholder weights have been obtained by carrying out an expert and a separate public MCDA survey. The surveys obtained preference weights for the electricity technologies, sustainability indicators within their indicator groups (techno-economic, environmental and social) and the sustainability aspects also. Three different methods were used for derivation of the preference weights. For the electricity technologies a rank based method was used, for the sustainability indicators, the SWING method was used, and for the sustainability aspects (techno-economic, environmental and social) the AHP method was used.

3.7 Summary

The decision-support framework used in this work takes an integrated and multi-criteria approach taking account all three dimensions of sustainability over the whole life cycle of the energy system(s). The use of MCDA guides stakeholders and decision-makers through the decision process, promoting transparency and allowing integration of their preferences with regard to the sustainability indicators. In addition, the iterative approach intrinsic in the framework makes the process dynamic and allows options and decisions to be reassessed and re-evaluated at any point.

The remaining chapters of this dissertation present the application of the decision-support framework through the steps outlined in this chapter.

4 Stakeholder Perspectives on the Issues Surrounding Electricity Generation: Expert Stakeholders

It is now common for governments and other large companies or organisations to involve stakeholders in their decision making process, especially when decisions are large and complex (see section 2.5). In these cases, there may be many alternatives, impacts and also many stakeholders who may be affected by or interested in the impacts of the decision. Government policy for achieving sustainable development now also includes principles which promote the inclusion of stakeholders within the decision-making process. These include ‘putting people at the centre’, ‘taking account of costs and benefits’, ‘using scientific knowledge’ and ‘transparency, information, participation and access to justice’ (DEFRA, 1999). Although these do not clearly state that stakeholder consultation is key to sustainable development, to achieve the four principles above, stakeholder consultation is compulsory. DEFRA’s 2005 sustainable development strategy then becomes more explicit in its aims, with its ‘using science responsibly’ principle seeking to ensure that ‘…policy is developed and implemented on the basis of strong scientific evidence, whilst taking into account scientific uncertainty…as well as public attitudes and values (DEFRA, 2005).

The debate surrounding energy policy is especially complex, controversial, emotive and one which almost everyone is certain to have an opinion on. Because of this, it is especially vital that stakeholders are included in the decision-making process wherever possible. Energy generation and availability brings with it economic prosperity, although there are also many negative impacts associated with all energy technologies. In addition to this, the views from stakeholders will differ greatly depending on their knowledge, perspective, beliefs and values (Payne *et al.*, 1992). As outlined in section 2.5, stakeholders may be grouped either as: anyone affected by the decision being made, including the public and ‘experts’ who provide advice during the decision-making process. Although it is often expected that expert stakeholders might be exempt from societal influence and biases with their increased understanding of the issues relevant to a particular problem, experts may also become ‘closed off’ to any other view point than their own. Indoctrination of certain ideas, ideals and views can occur because of stakeholder expertise within a particular and/or specific area of the decision problem.

Despite accepting that all persons are open to bias and cannot be purely objective in their approach, it is widely acknowledged that a thorough expert consultation before implementing a policy, strategy or making a decision is an integral part of any decision-support framework (Madlener and Stagl, 2005; Alberts, 2007; Madlener *et al.*, 2007).

The long-term goal of a stakeholder consultation exercise is often to achieve consensus among stakeholders through increased understanding of the issues associated with decision alternatives. Although this is difficult to accomplish, the participatory process leads to a greater understanding of others' viewpoints, through which trade-offs can be made to reach either an agreed course of action, or at least an appreciation of others' perspectives, even when consensus is not reached. Before the 'group decision making' stage of decision analysis is reached, the issues associated with the decision problem must be clearly understood. The exchange of information between experts and decision analysts will lead to a more robust decision-support framework and therefore increased competency of decision making (Steelman and Ascher, 1997). In addition, increased public understanding of the issues associated with power generation through knowledge sharing and transfer increases awareness of the 'real issues' associated with power generation amongst and an ability to weigh up the pros and cons of different power options.

This chapter focuses on the expert stakeholder engagement that has taken place as part of this research and details the findings from the consultation process. The next chapter focuses on the public consultation process also carried out as part of this work and presents the findings from two public consultation exercises.

4.1 Aims and Objectives of the Expert Consultation Process

The overall aim of the expert consultation was to identify the main issues associated with the sustainability assessment of nuclear power in the UK electricity mix (focussing on technical, economic, environmental and social impacts). The specific objectives include:

- to engage with as many as possible divergent stakeholders associated with nuclear energy and other energy technologies within a given time frame;

- to identify which sustainability indicators are most and least important to the stakeholders in assessing the sustainability of nuclear power in an the UK;

- to identify further sustainability issues or indicators that had not been previously considered;

- to identify any disparity between stakeholder group views on how the sustainability of nuclear power in the UK should be assessed; and

- to identify stakeholder perceived drivers and barriers to nuclear and other electricity options and systemic issues and challenges associated with the evaluation of energy systems.

The expert consultation process was carried into two stages. The first involved consultation on the issues and indicators to be considered within the decision-support framework and helped to finalise the set (43) indicators to be included within the decision-support framework. The second stage considered asked the expert stakeholders to elicit preferences on the 43 indicators using MCDA. The methodology used in the first stage is outlined in the next section followed by the findings of the consultation in Sections 4.1.2- 4.1.4. The second stage of expert consultation is discussed in Section 4.2.

4.1.1 Stage 1 research methodology

The consultation exercise has sought to examine stakeholders' views on the indicator framework developed as part of the SPRIng project (Stamford and Azapagic, 2011). The final indicator framework is described in more detail in Section 3.5. The initial indicator framework presented to stakeholders was presented as separate economic, environmental social and technical aspects. In total, there were initially 59 proposed indicators of which 19 were environmental, 14 were economic, 19 were social and seven were technical. This initial first draft of the indicator framework methodology can be found in the first stakeholder questionnaire in Appendix 2. Details about the specific decisions taken on the exclusion or changes made to several of the sustainability indicators can be found in PhD thesis of Stamford (2012).

A mixed-methods approach was selected for the stakeholder consultation exercise including qualitative interviews and quantitative questionnaires. This has produced a mixed bottom-up, top-down methodology, with information being reviewed and compiled on the impacts of nuclear power and other electricity generating technologies a priori and expert opinion on the defined measures sought through questionnaires and semi-structured interviews. Based on the grounded theory method of unstructured data analysis (Glaser and Straus, 1967), the semi-structured interview data allowed identification of key issues associated with energy modelling and sustainability analysis following the decision-support methodology presented in Chapter 3. The decision to use a semi-structured approach is based on the fact that much work has been carried out over the last decade focussed on the development of sustainability assessments and sustainability indicator sets for a variety of sectors – therefore presentation of a developed indicator set designed for use to compare nuclear power against alternative electricity-generating technologies was chosen, resulting in a mixed-methods approach. Research on the applicability of several sets of sustainability indicators in assessing the sustainability impacts of nuclear power in the UK had been carried out by Stamford (2012) before the interviews took place; it is this research that formed the basis of the stakeholder interviews.

4.1.1.1 Stakeholder sample

In addition to nuclear energy stakeholders, a wider sample of stakeholders were identified as essential to sample in order to be able to assess nuclear power in the context of the UK electricity mix. In October 2009, a comprehensive list of around 100 organisations, private companies and government bodies were identified as valuable consultees. The bodies were then approached to ask if a representative from the company/organisation would be willing to meet with researchers from the SPRIng project to discuss the sustainability assessment of nuclear power, namely, the indicator framework. In addition to the supplementary bodies identified, representatives from the SPRIng project Steering Committee and researchers from the SPRIng project were also asked if they would be willing to meet to discuss the project’s work on sustainability indicators.

In total, 32 individuals took part in the consultation process representing 24 different organisations. Of these participants, the following response rates from different organisation types are observed:

- Associations – 10% response rate (20 invited, 2 participated)
- Consultancy – 100% response rate (4 invited, 4 participated)
- Energy supply industry – 55.6% response rate (9 invited, 5 participated)
- Government agencies – 50% response rate (10 invited, 5 participated)
- International organisations – 50% response rate (2 invited, 1 participated)
- NGOs – 21.4% response rate (14 invited, 3 participated)
- Regulators – 50% response rate (4 invited, 2 participated)
- Academia/research organisations – 91% response rate (11 invited, 10 participated)

A briefing document was produced for those respondents who had not previously been aware of the SPRIng project. The briefing document (Appendix 1 SPRIng Briefing Document) summarised the rationale for the SPRIng project, its main aims and objectives, the project's progress and duration and the work that was being carried out at the time that the document was produced. The idea behind this was to put all of the stakeholders who were being consulted on an 'equal footing' before going ahead with the consultation process. The main aim of this was to minimise any bias in knowledge of the project, so that the feedback on the indicator framework would come from individuals who shared the same level of information on the indicators as each other. In addition, another aim was for the stakeholders to be informed about the indicators (how they were measured, where the data has come from and understanding their impacts) as possible. Therefore, by explaining the project in this way prior to consultation, the meeting could then focus on gaining the desired feedback, rather than explaining the project context and aims.

4.1.1.2 Questionnaire development

A questionnaire was developed (Appendix 2 SPRIng Expert Stakeholder Questionnaire) which included Likert-style questions seeking to assess how important each stakeholder believed each sustainability indicator (as part of the indicator framework) to be in assessing the sustainability of nuclear power and other energy options as part of the UK electricity mix. Each question was situated on a four-point Likert scale with '1' representing a response of 'not important', '2' 'slightly important', '3' 'important' and '4' 'very important'.

In addition to the quantitative Likert-based responses, the stakeholders were also asked for qualitative feedback, as below:

1) Please provide any feedback and comments for each of the indicator sets (environmental, economic, social and technical) and suggest any additional indicators that you think might have been missed.
2) Does your company collect/hold any data/information which would be useful in evaluating the indicators that you may have suggested as part of the previous question? If so, please provide the details.
3) Does your company collect/hold any data/information which would be useful in evaluating the indicators presented in this questionnaire? If so, please provide the details.
4) With respect to the decision-support framework and sustainability assessment of different energy options, what kind of question would you like to be able to ask? What should we include in the decision-support framework?

The motivation for including question (1) in the questionnaire was to elucidate any opinions on particular indicators that stakeholders might feel strongly about, or any reasons why indicators were believed to be important or unimportant in the sustainability assessment of energy options. As the stakeholders that took part in the consultation process often came from companies and organisations relevant to the nuclear industry (and other energy industries), they were also asked if they had access to any data sources that might be relevant in quantifying the indicators as part of questions (2) and (3). Finally, the stakeholders were asked what kind of information they would want out of the decision-support framework, i.e. what would they like to be able to ask/enquire about in order to compare the sustainability of nuclear power against other energy options.

4.1.1.3 Data collection

Samples were collected in the form of semi-structured interviews with each stakeholder. As part of the sampling strategy, the representatives from the organisations/companies were usually targeted as the CEO/director/head of the company organisation in order to elicit views that were likely to be most representative of the company or organisation or most influential, given the application of the decision-support framework. Therefore, most of the stakeholders consulted represented a similar level of standing within their workplaces. Each organisation or company represented was sampled separately to ensure that the perspective sampled was as representative of their organisation as possible, without any influence from others.

A total of 29 meetings took place between January and June 2010 in which 35 representatives were met (in some cases, more than one company representative attended the meeting). To maximise participation, the experts were offered for the interview to be carried at their place of work.

The feedback elicited from the experts through the consultation process can be considered as potentially high power/influence stakeholders. Figure 4.1 displays a power versus interest matrix, with interest and power dimensions. Interest is in the problem, or issue which is being resolved, and power is the potential of a stakeholder to influence or shape the problem's outcome (Bryson, 2004).

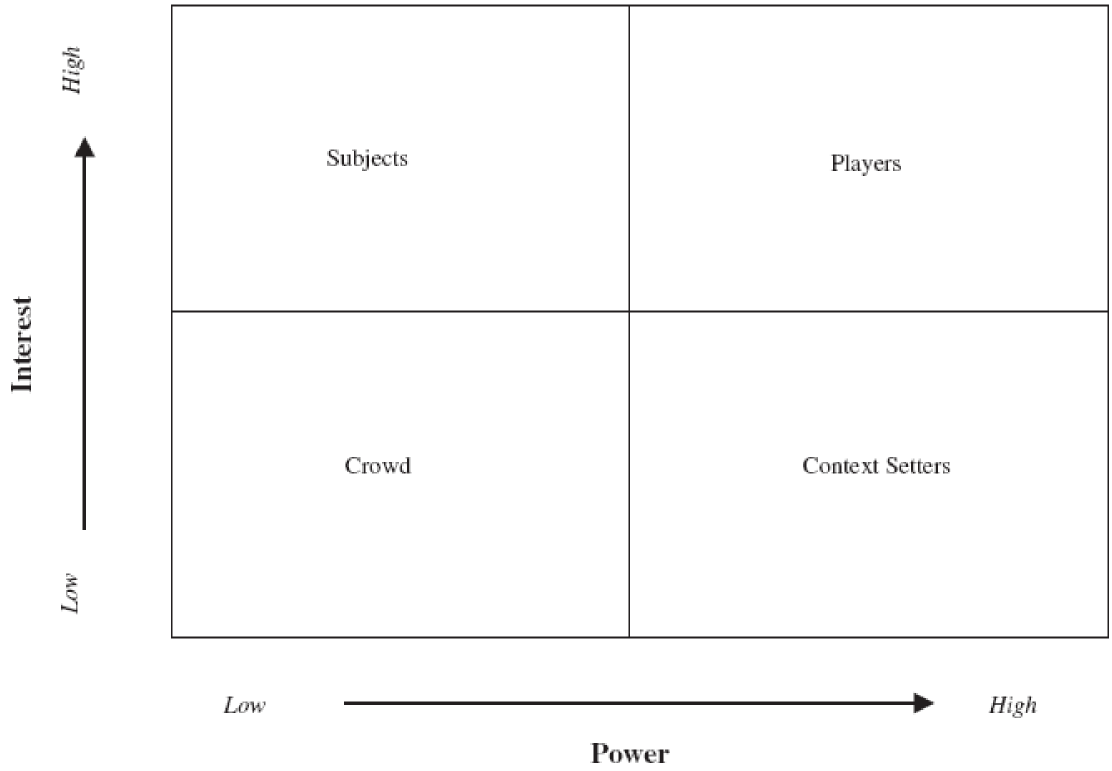


Figure 4.1. Power versus interest grid (Eden and Ackerman, 1998).

By comparison, the public would represent a low interest, low power group on the power versus grid matrix. The stakeholders consulted as part of this exercise would be considered relatively high interest and high power. The 'players' in the nuclear decision-making context would usually be represented by Government, who are the key decision-makers in energy policy. However, the first problem that is being assessed as part of the stakeholder consultation is not on nuclear power's sustainability, but the way in which nuclear power should be assessed against other energy options and as part of an energy mix.

4.1.1.3.1 Interview approach

The meetings took the format of a semi-structured interview and lasted between one and a half to two hours. After any initial questions that the consultees had answered, the indicator framework was presented to the interviewee. Each indicator was then explained, with a description of what is was measuring, how it was being measured and why it was being measured. Any questions that the interviewees had regarding the indicators were also answered. As the stakeholders were from a range of varying sectors (not always directly associated with nuclear power), questions and discussions were asked around the individuals' area of expertise. Thorough notes were taken throughout the interviews which detailed the consultees' comments on: the proposed indicators; the SPRIng and framework methodology; drivers for and barriers to nuclear power in the UK; use of the framework methodology; additional issues to take into account.

The interviewees were then presented with the 'SPRIng questionnaire' and asked to complete post-interview as meetings were often limited to two hours and this time was needed in order to thoroughly explain the indicator framework, so that the interviewees understood what they were rating in the questionnaire. Respondents chose whether to complete by paper and send back in the post, or electronically and send back by email. All interviewed stakeholders agreed to complete the questionnaire. The stakeholders were asked to send back the questionnaire within two-three weeks. This amount of time was given to complete the questionnaire as the representatives met with were often busy due to their positions within the company they were speaking for. A reminder email was sent out to non-respondents three-four weeks after the meetings to increase the response rate. Out of the 35 representatives met, a total of 26 questionnaires were completed and returned. This is a response rate of 74.3%, which is relatively high. However, due to the interest of the stakeholders in the SPRIng project and meeting with the researchers personally, this level of response is perhaps not unexpected.

4.1.1.3.2 Theoretical frameworks

The considerations for this interview approach include the development and innovations to a sustainable electricity supply for the UK, and the influence that nuclear power may or may not have in contributing to the goal of sustainable development in the electricity sector. A whole systems or transitions approach for the review of this is adopted, with the recognition that "new markets, user practices, regulations, infrastructures and cultural meanings" (Geels *et al.*, 2004) are borne from wide-ranging approaches across technologies, rather than being confined to individual technologies. During interviews, the participants were encouraged to discuss issues from across the whole system of electricity generation, with bias avoided by asking broad, open questions initially to prompt interviewees' own assessments of the major issues.

Coevolutionary approaches (complementary to transitions approaches) describe the way in which two or more systems developing alongside each other help to shape the other system(s), due to the bounds of rationality (explained by evolutionary economic theory) exhibited by actors in the system or systems. In this case, the individual systems are the different methods of electricity generation, and the drive to a more 'sustainable' electricity mix are giving rise to all the issues discussed by the stakeholders in the expert interviews. The stakeholders consulted (or actors within the field of electricity-generation and policy decision-making) display limited rationality, as their fields of expertise within the system of electricity generation are bounded by their own experiences. Therefore, by taking into account the perspective and opinion of a variety of actors within the system, predictions of drivers and barriers to implementation and innovation of various electricity-generating technologies (which are influenced by changes and development of other electricity-generating technologies) can be made.

4.1.2 <u>Quantitative survey findings</u>

4.1.2.1 Stakeholder demographic

Of the 26 questionnaires completed, males accounted for 96% of the responses (25 counts) and females 4% of the responses (one count). The stakeholders were classified into different stakeholder groups to determine if there was any disparity in responses between stakeholders groups. These groups are: academia (31.3% of responses), energy supply industry (15.6% of responses), government agency (15.6% of responses), consultant (12.5% of responses), NGO (9.4% of responses), association (6.3% of responses), regulator (6.3%) and international organisation (3.1% of responses). The contributions of these can be seen in Figure 4.2.

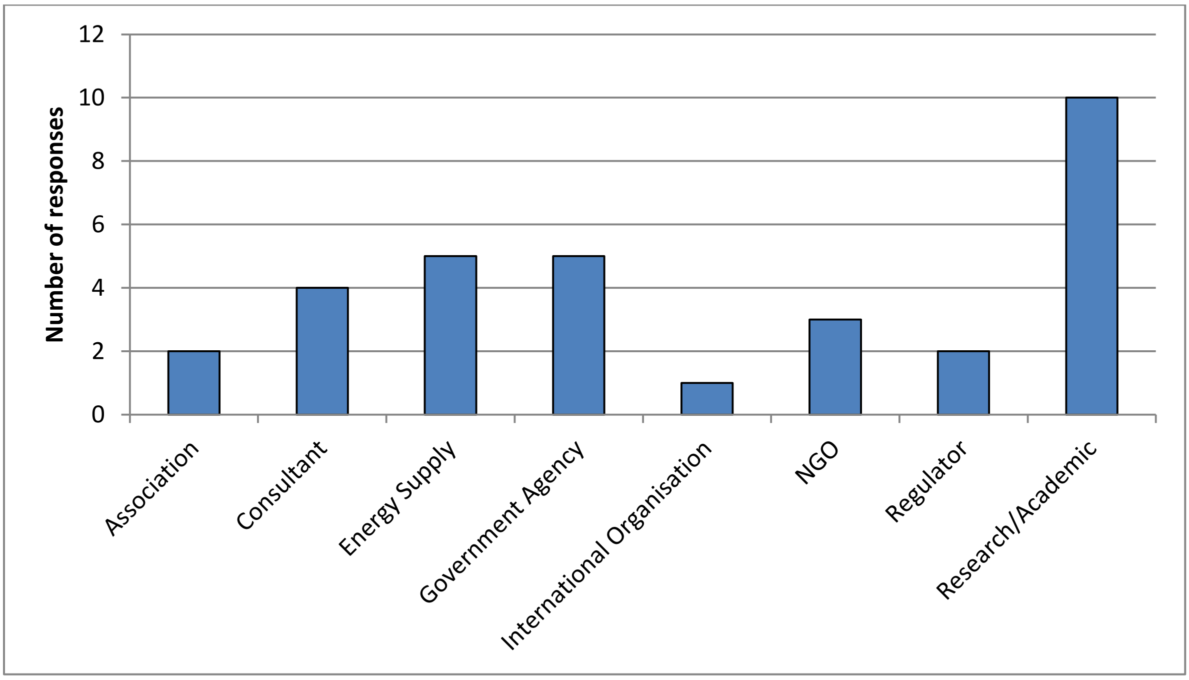


Figure 4.2. Stakeholder group demographics by organisation type.

4.1.2.2 Total sample results: sustainability indicators

The stakeholders who took part in the interview process were asked to rate the 59 sustainability indicators on a Likert-based scale. As mentioned earlier, the Likert scale was a four-point, forced choice scale, with a response of 1 representing ‘not important’, to 4 representing ‘very important’. Taking the overall mean indicator scores into account, the stakeholders rated 25 (42%) out of the 59 indicators as important or very important in assessing the sustainability of nuclear power and other energy generating technologies. Only one of the indicators (percentage of mining sites with ‘fly in, fly out’ operations) was given an average rating of less than 2.0, with an average rating of 1.8. The total average ratings and the rating from each stakeholder group are summarised in Table 4.1. The overall average rating for all stakeholders and indicators was 2.9. The academic group average displayed ratings of important or very important for 36 indicators and two indicators given a rating of less than 2.0. The industry group gave 30 indicators a rating of important or very important on average and rated one indicator with a score of less than 2.0. The utility stakeholders rated 38 indicators as important or very important and two with a rating of less than 1.0. The regulators gave 32 indicators and important/very important rating and six indicators were rated with a score less than 2.0. The research organisation and non-governmental organisation groups only had one member within each of the groups, therefore there is no average score for these groups. However, the respondent in the research organisation group rated 23 of the indicators as important/very important and gave five indicators a score of less than 2.0. The individual in the NGO group rated 44 of the indicators as important/very important and nine indicators were given a rating of less than 2.0.

The academic group gave the highest average rating for all indicators (3.00), followed by the utility group, then industry (2.95) NGO (2.83), regulator (2.75), international organisation (2.50) and the lowest average score was the research organisation group (2.46).

The theme which received the highest average rating from all stakeholder groups was technical indicators (2.97), followed by the environmental indicators (2.93), then social (2.89) and finally economic with the lowest average overall rating (2.84). The economic indicators averaged out at the lowest rating due to the dominance of the stakeholder sample from academia, this group gave the economic the second-lowest average rating (after international organisation) of 2.29 and dominated the stakeholder sample (31.3% of those interviewed worked within academia). Environmental indicators were valued most highly by the academic group; economic indicators were valued mostly highly by the industry and regulator groups; social indicators were valued most highly by the industry group and the technical indicators were valued most highly by the utility group. The order of sustainability theme preference for each of the stakeholder groups is as follows (with average scores in brackets):

- Academia (environmental [3.15], technical [3.05], economic [2.94], social [2.89])
- Industry (social [3.17], technical [3.02], economic [2.96], environmental [2.71])
- Utility (technical [3.29], social [2.92], environmental [2.82], economic [2.79])
- Regulator (technical [3.00], economic [2.96], environmental [2.68], social [2.58])
- International Organisation (environmental [2.79], social [2.50], technical [2.50], economic [2.11])
- Research Organisation (environmental [2.74], technical [2.43], social [2.32], economic [2.29])
- Non-Governmental Organisation (environmental [3.11], social [2.74], economic [2.71], technical [2.57])

Despite the observed discrepancies between average ratings of the indicator groups by the individuals defined within organisation type, in reality these differences are small and the sample size of stakeholders consulted is also relatively small for a statistical difference in opinion to be observed. In order to confirm or contradict the finding outlined above and in Table 4.1, a larger sample size from all organisation types would be needed.

Table 4.1. Average stakeholder responses across all indicators and sustainability themes by stakeholder category.

	Respondent Groups							
	All Stakeholders	Academia	Industry	Utility	Regulator	International Organisation	Research Organisation	Non-Governmental Organisation
Average Rating - All Indicators	2.90	3.00	2.95	2.97	2.75	2.50	2.46	2.83
Average Rating - Environmental Indicators	2.93	3.15	2.71	2.82	2.68	2.79	2.74	3.11
Average Rating - Economic Indicators	2.84	2.94	2.96	2.79	2.96	2.11	2.29	2.71
Average Rating - Social Indicators	2.89	2.89	3.17	2.92	2.58	2.50	2.32	2.74
Average Rating - Technical Indicators	2.97	3.05	3.02	3.29	3.00	2.50	2.43	2.57

4.1.3 Qualitative interview results

As described in the interview methodology section, the interviews with the expert stakeholders were carried out in a semi-structured manner. The notes from these interviews were then typed-up and transcribed within the qualitative software program, NVivo (version 9.2). The use of this software allowed the information gathered to be ordered into themes and specific issues to be identified. The seven main themes under which the discussions with the expert stakeholders have been classified under the following:

- important issues and indicators to take into account;
- unimportant/insignificant issues and indicators;
- additional issues and indicators to take into account;
- drivers to and barriers for nuclear and other technologies; and
- systemic issues and challenges.

4.1.3.1 Perceived important issues and indicators

The ‘top ten’ most important issues rated by the stakeholders in the quantitative survey can be observed in Figure 4.3. The most important issue determined from the quantitative survey on the importance of the indicators was, on average across the experts, voted as ‘global warming’. This was then followed by ‘radioactive waste production’, ‘number of large accident fatalities’, ‘total cost of electricity’ and ‘lifetime of fuel reserves’. The sixth most important rated indicator rated by the stakeholders is ‘radioactive waste management’, followed by ‘capital costs’, ‘total radiation’, ‘imported fossil fuel avoided’ and finally, at number ten is ‘human toxicity potential’.

Again, as with the least important indicators, stakeholders were not specifically asked about their views on the importance of the indicators in the interviews. Analysis of the interview feedback showed that themes could be drawn out on groups of indicators that were discussed and highlighted as important to the stakeholder(s) in the assessment of the sustainability of various electricity-generating technologies. From analysis of the stakeholder interviews, importance of indicators tended to focus on the ‘big issues’ already associated with electricity generation (such as global warming) and specifically, controversial issues associated with nuclear power, such as radioactive waste production, radioactive waste management and radiation dose to public and workers.

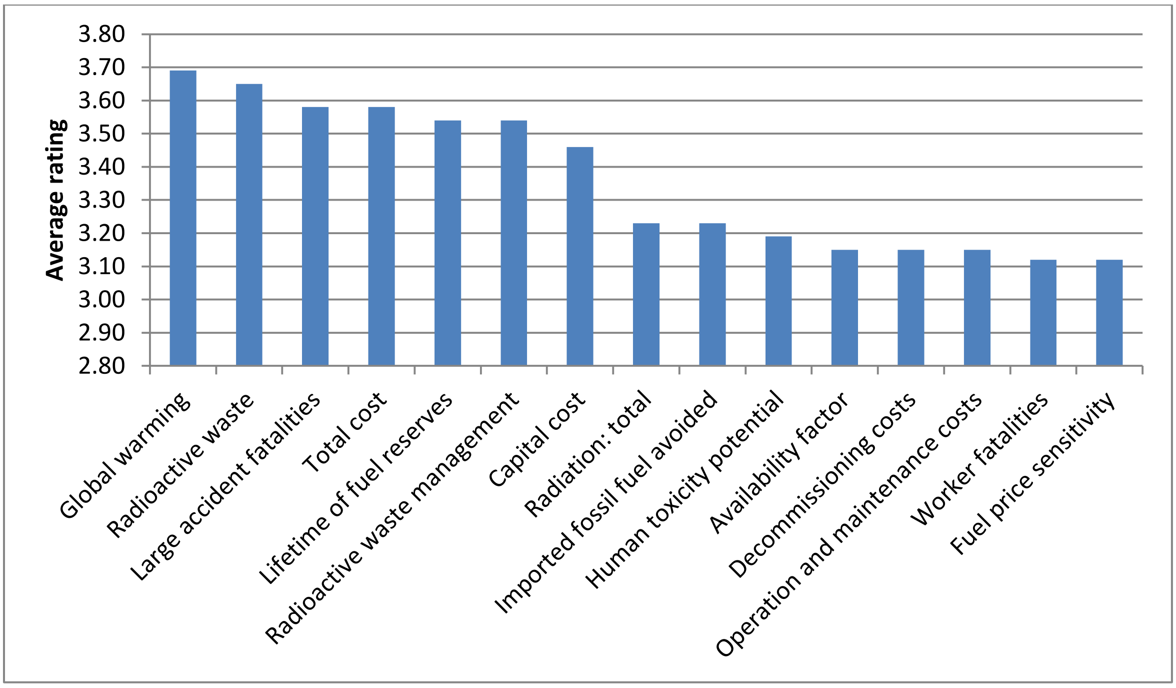


Figure 4.3. Top fifteen most important indicators identified through the expert stakeholder consultation process. 1 – not important; 4 – very important. Please note, the y-axis does not begin at zero as this does not allow to distinguish between the different ratings of the indicators.

Global warming was not specifically discussed by many stakeholders during the interview process. This is largely attributed to the acceptance of the importance of this issue globally and the huge challenge faced by many nations in lowering the carbon intensity of energy provision and electricity production.

The feedback regarding the production of radioactive waste determined that although all stakeholders thought that this was an important issue, the reasons for identifying it as such varied considerably. For example, some stakeholders believed that the human health and environmental detriment posed by radioactive waste production was a serious concern, whilst others believed that the actual detriment of radioactive waste would be low, but societal concern for this issue meant that the discussion of its impact should be at the forefront of the nuclear power debate. Radioactive waste management was also rated as highly important, being voted, on average, as the sixth most important sustainability indicator to consider. Stakeholders believed the importance of this issue related to the fact that special arrangements for waste management have to be made and are not yet fully determined, and also that large volumes of radioactive waste would potentially be difficult to manage. In addition, a third indicator related to radiation was ranked as the eighth most important indicator to consider and this was ‘total radiation’. This was highlighted as an important indicator again due to public fear and perception of radiation impacts on humans and the environment.

Large accident fatalities was voted as the third most important impact to consider in the sustainability assessment. Many of the public fear deaths from large accidents, especially in terms of nuclear power generation and public acceptability of this impact was listed as an important obstacle to overcome in terms of acceptance of various electricity-generating technologies.

The total cost of generation from the variety of technologies and the need for technologies to be ‘affordable’ is a pre-requisite of power generation from a particular source. This includes competition globally, in order to ensure energy security for the UK by domestically-generated power. Therefore, affordability is an issue for utilities, Government as well as consumers. Capital cost was also rated as an important indicator, and the ‘main cost driver’ for the development of many types of power stations and installations due to the impact that this cost has on investors.

Durability and longevity of technologies with non-renewable fuel resources is also a very important sustainability issue and is rated as the fifth most important indicator. This indicator has large bearing on investment decisions and technological development in various technologies. For example, future generation nuclear power stations developed to use reprocessed fuel and fast reactor that have a closed fuel cycle would make nuclear power much more sustainable under this indicator.

Finally, human toxicity potential is rated as the tenth most important indicator to consider in the sustainability assessment of competing electricity technologies. This includes toxicity from non-radiological sources.

4.1.3.2 Perceived unimportant issues

The ‘bottom ten’ unimportant issues rated by the stakeholders in the quantitative survey can be observed in Figure 4.4. The least important issue determined from the quantitative survey on the importance of the indicators was, on average across the experts, voted as ‘percentage of mining sites with fly-in, fly-out operations’. This was then followed by three more indicators developed to take into consideration the impacts on local communities from electricity generating power stations or installations, including: proportion of management hired from local community; involvement in community projects; and proportion of spending on local suppliers. The sixth least important rated indicator is also one which takes into account local community impacts – specifically the direct payments made to local communities from electricity generation operations. The focus on the local community indicators as being unimportant in the assessment and comparison of electricity-generating technologies is also evident from the transcripts of the interviews with the stakeholders.

Stakeholders were not specifically asked about their views on important/unimportant indicators in the interviews. This means that interviewees might have thought the indicator straightforward to measure and overlooked its importance in the interview, but then rated some of them as unimportant later as part of the questionnaire. Analysis of the interview feedback showed that themes could be drawn out on groups of indicators that were discussed and highlighted as little use/unimportant to the stakeholder(s) in the assessment of the sustainability of various electricity-generating technologies. Unimportance can cover a variety of issues with the indicators. For example, data collection for certain indicators is thought to be particularly difficult and therefore a meaningful analysis of the impact would not be possible, some indicators may be particularly hard to define in terms of which measures to use (this is especially the case with many social indicators), assumptions that the public would not be interested in certain indicators is also made, and the measurement of some indicators may allow little differentiation between the various technologies. It is interesting to note that many of the indicators listed in the bottom ten are social measures, and of the economic indicators in the list, they are specifically those which relate to more social impacts, such as health and safety fines, spending on local suppliers and payments to local communities. Two of the bottom ten indicators are environmental measures (total water use and use of abiotic resources).

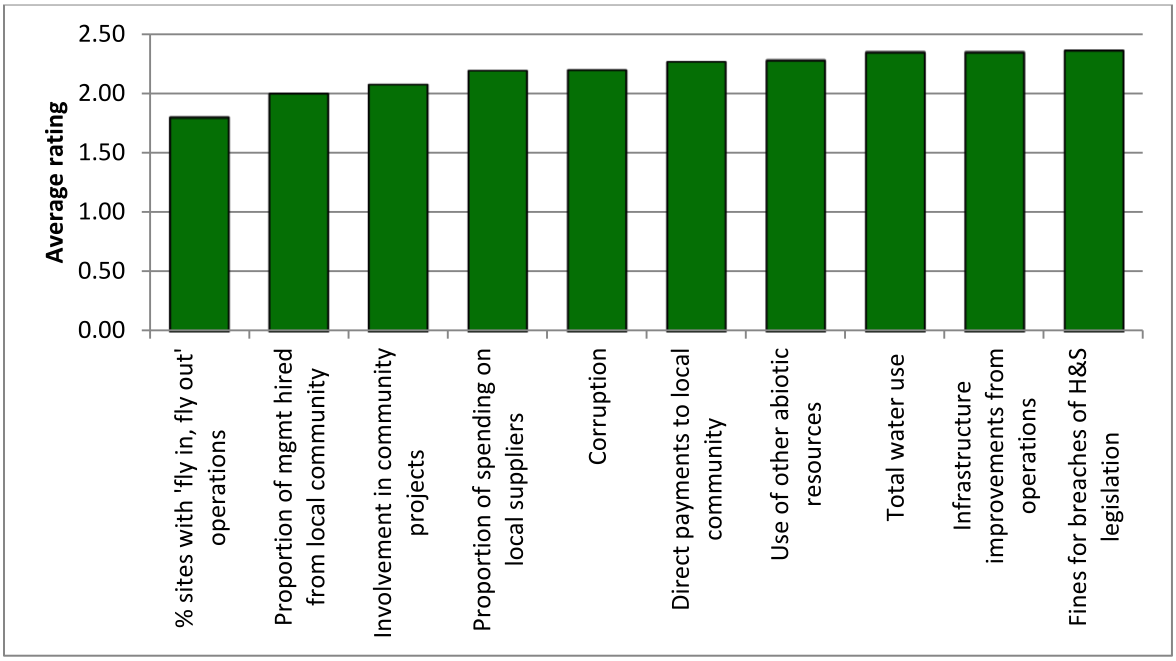


Figure 4.4. Bottom ten least important sustainability indicators identified through the expert stakeholder consultation process. 1 – not important; 4 – very important.

Review of the interview feedback on the indicators gives several indications as to why the local community set of indicators have been rate as unimportant. One interviewee voiced the opinion that the local impacts were "*only relevant in 'local license to operate' terms*", implying that agreement and engagement between the utility and the local community before planning consent is given. The utility will enable good corporate relations with local communities in order to gain a competitive edge over others in the marketplace. Therefore, measurement of local impact indicators during the operational lifetime of a power plant may be seen as superfluous as the local community has already entered into a mutually beneficial agreement with the operator. Additional reasons for the low rating of these indicators includes the belief by the stakeholders that the UK public do not consider and are not interested in the local community impacts of different power station or installations when evaluating their overall impact and that measurement of local impacts for only the operational stage of the life cycle would give false results as construction, mining, fuel fabrication and decommissioning, etc., also have impacts on the local communities in which these operations are carried out.

Corruption was rated as the fifth least important indicator to consider in a sustainability assessment of electricity-generating technologies. Reasons for this indicator being rating as low on the importance list vary from reasons of denial that corruption would be happening within the supply chain of nuclear power and other electricity-generating technologies, that the issue is too controversial to include in the assessment and that the impact for this indicator would not differ across technologies. Corruption was originally designed to measure ‘improper business dealings’ across the supply chains of the competing electricity technologies. A significant proportion of stakeholders believed that it is a “*pre-requisite for business*” for all transactions to be non-corrupt and therefore this issue is irrelevant to nuclear power and other methods of generating electricity. Another issue with this measurement is the ability to obtain data on improper business dealings throughout the whole supply chain of all electricity-generating technologies. The data on this measure is likely to be non-existent, at best patchy and unreliable. Despite the sceptical view expressed by some stakeholders on measuring corruption within the fuel cycle of different technologies, it was decided that, with revisions and simplification, a measure of corruption was needed surrounding this important ethical issue so that this indicator was retained in the final set of the indicators.

4.1.3.3 Additional issues and indicators

Feedback on the indicator set from the stakeholders also included the option of each interviewee to suggest measures that they believed were missing from a comprehensive sustainability assessment of electricity options, and/or additional uncertain issues that should be taken into account in the energy scenario assessment. Additional suggested measures/indicators are presented below in their sustainability categories (economic, environmental, social and technical) and finally, additional issues with high levels of uncertainty (i.e. that can’t be measured as part of a meaningful sustainability assessment) are presented and discussed.

4.1.3.3.1 Economic indicators

Carbon price and subsidies

The price of carbon and the design of the carbon market will have a critical impact on how viable it makes low carbon technologies, including nuclear. Several stakeholders highlighted this issue and expressed a desire for this to be incorporated in the economic aspects of the decision-support framework. In addition to the carbon price, other subsidies or "*guaranteed access to the grid*" measures were also highlighted as aspects of different technologies that should be included in the sustainability assessment.

Return on investment

It was believed amongst several stakeholders that the "*rate of return on investment would be a better indicator* (than levelised cost of generation)…*the market will greatly affect the revenue* (from the variety of electricity generating technologies)".

Economic risk

The economic risk of investment in a technology was suggested as an additional economic indicator. The economic risk for nuclear power could be considered greater for utilities to invest in as "*a nuclear accident would kill nuclear in the UK*". Accidents at other power stations or resulting from generation from electricity generating installations tend to cause small-medium scale injury and death, whereas the fear factor associated with nuclear power (even if the accident wasn't a large one) could result in disproportionate negative opinion on nuclear power in the UK.

4.1.3.3.2 Environmental indicators

Radiation dose to the environment

Many stakeholders raised the issue of quantifying the impacts of radiation doses to the environment. This includes the radiological effect on environment and sensitivities of ecosystems to radiation.

Localised impacts

Localised environmental impacts were also a very prevalent issue raised among the stakeholders during the consultation exercise. Impacts on Sites of Special Scientific Interest, biodiversity, protected sites and protected species were raised as important aspects to consider within local ecosystems and landscapes. In addition, localised noise pollution and visual impacts of power stations or electricity generating installations were suggested as additional local environmental impacts that would be useful to consider when comparing electricity scenarios or technologies.

4.1.3.3.3 Social indicators

Skills and expertise

Levels of employment induced by the variety of methods of electricity generation are included in the indicator framework – higher levels of employment are preferable for social wellbeing across the country. However, several stakeholders also indicated that although as a society we prefer employment levels to be as high as possible, in some cases expertise and skills are not prevalent enough to support certain electricity generation programmes. In this case, expertise would need to be imported from countries which display high competency levels for the chosen technology or technologies.

High level waste repository

A high level waste repository is still to be identified for high level radioactive waste storage in the UK from nuclear power generation. The largest obstacle to overcome in determining the site, or sites for storage is identification of a suitable site (in terms of geology and location) that is volunteered for use by the local authority.

Terrorism

The terrorist risk of having nuclear installations was suggested as an extra indicator to assess nuclear against alternative electricity options.

Public opinion

Public engagement and the need to gauge views on impacts in and around power plant operations and other activities throughout the life cycle.

4.1.3.3.4 Technical indicators

Nuclear supply chain

If certain technologies in the future are pursued by the Government at a much higher implementation rate that current operation, supply chain capabilities would need to be assessed in order to determine whether these technologies can be built and operated on a large scale.

National grid

A number of stakeholders interviewed believed that capability and resilience of the national grid under a variety of electricity scenarios should be considered. New power lines would need to be added to the current transmission system if the future energy mix changed considerably to a decentralised mix, for example. The number of lines, their extent and location may are all open to change depending on these factors.

4.1.3.3.5 Additional issues

Economic

The implementation of a ‘smart grid’ would also affect the transmission system and impact the grid across Europe and in the UK market – therefore this should be taken into account in future electricity scenario assessment.

Risks of different market structure is also a big issue that could change significantly the economics of the power system (e.g. more competition on renewables would mean lower costs over time and more security). A monopoly on a fuel/technology could mean a higher price. Would the economic indicators be effective in assessing conditions in a nationalised versus privatised energy system?

Environmental

The sensitivity to sea-level rise of nuclear power plants is an important potential future development that could significantly affect the operability of nuclear power plants due to their proximity to the coast in most cases in the UK.

Social

Increased death rate from hot summers/cold winters (with rising energy costs) is something that is important to take into account with projections of future electricity costs and is also high on public concern.

The political and economic impact of investment in electricity markets in the long and short term and the effect of Government influence should be considered. The Government can override economic aspects by completely supporting a particular technology (through tax investments). A liberal economy would not support nuclear, as nuclear power needs government intervention and support at some stages of its life cycle.

Technical

Future reprocessing of spent fuel in the UK is something that should be considered as this can impact positively and negatively on many other aspects of a sustainability assessment.

4.1.3.4 Drivers and barriers

The national-level drivers and barriers for nuclear power have already been identified as part of the SPRIng project (see Greenhalgh and Azapagic, 2009). The main drivers for the Government to press ahead with nuclear power were identified as security of energy supply and climate change. The perception of nuclear power by stakeholders and planning consents were identified as the main barriers. The changing status of some barriers to nuclear power to facilitate a new generation of power plants, such as the economics of nuclear power, public perception and the waste management policies for nuclear waste were also discussed.

Part of the aim of this stakeholder consultation was to identify additional drivers for and barriers to nuclear power, in addition to those already discussed above. Government policy often focuses on the ‘top level’ drivers or barriers to a particular method of electricity generation, and focus on the operational-level detail is often left out of Government discussions and publications. A co-evolutionary approach to nuclear power penetration is taken, with views from nuclear experts, in addition to experts from a variety of organisations associated with other electricity options and the sustainability of energy generation (including economic, environmental and social perspectives) to ‘paint a picture’ of the future of nuclear power generation and the implications of a low or high penetration of nuclear power in the UK’s electricity mix.

Interviews with the stakeholders revealed four main themes to drivers and barriers to various electricity-generating options for the UK: barriers to nuclear power; barriers to other electricity-generating options; drivers for nuclear power; and drivers for other electricity-generating options. In some cases, interviewees did not elaborate on the reasons for believing certain issues constituted significant barriers to or drivers for certain electricity generation methods. In these cases, a discussion around the driver or barrier is undertaken in order to give context to the issue. The feedback from stakeholders consulted on this project is discussed under these headings below.

4.1.3.4.1 Barriers to nuclear power

The barriers to nuclear identified by stakeholders broadly fall into the indicator categories, as the discussions in the interviews were mainly based on the development of indicators to assess sustainability of nuclear and electricity generation in the UK. In addition to barriers under the indicator headings within the sustainability categories (economic, environmental, social and technical), additional barriers were also identified and are discussed at the end of this section.

Technical indicators

Dispatchability

In the UK, nuclear power stations are used for base load provision of electricity. The economics of nuclear power means that it is favourable to run nuclear power stations at high capacity continuously, with shut downs only planned for re-fuelling. In France, the high penetration of nuclear power into the French electricity mix means that (even with pumped storage) some nuclear reactors need to shut down at times of lower electricity demand, making them less economic than is desirable. It is likely that future generations of nuclear power plants will have a load-following capability, but until then, it is unlikely that the UK would pursue such an ambitious target for nuclear power penetration with the current economics of nuclear power and their inability to be as flexible and dispatchable and gas and coal-fired power stations. This was identified as a potential issue in the large-scale deployment of nuclear power in the UK during the expert stakeholder interviews. However, several stakeholders also believed that future nuclear would display the load-following ability as mentioned above, and therefore minimising this potential barrier.

Economic indicators

Environmental costs

Environmental costs for nuclear power generation include any capital spent on environmental protection during UK-based operations of the nuclear power industry (i.e. operation, decommissioning, waste storage and disposal). In the opinion of several stakeholders, it is believed that environmental protection and the costs of environmental protection in particular could be detrimental to the development of nuclear power in the UK. For example, EDF have encountered problems at their Hinkley Point site due to the need to relocate a community of badgers living on the site of the proposed Hinkley Point C power station. This was discussed in one of the stakeholder interviews and the interviewee pointed out that the operator of the site (in this case EDF) would be unlikely to meet their (then) 2017 deadline (WNN, 2012) for operation of the power plant. In addition, another interviewee stated that 'excess spend on environmental costs could be crippling' (to nuclear power). The Hinkley Point C nuclear reactor Generic Design Assessment (GDA) process and planning works have been significantly delayed (WNN, 2012) by at least two years largely due to external events from the Fukushima disaster and subsequent protests and demonstrations, but also due to smaller site-specific incidents and contractor issues. The wider point demonstrated here is that delays and additional costs to one or more nuclear power stations increase an already large burden on this electricity generation method, meaning that nuclear power specifically is very sensitive to extra spending and delays in construction due to unforeseen circumstances.

Health and safety costs

Related to additional environmental costs is the indicator for 'fines in breaches in health and safety legislation'. From the interviews conducted with experts that worked in the nuclear industry or were strongly associated with it, a theme of their belief of over-regulation in the nuclear industry was apparent. This led to a feeling that costs in the field of health and safety were disproportionate to the actual detriment in health from nuclear power generation. In addition, some of those not associated with the nuclear industry pointed out that many nuclear power plants had been fined at some point over their lifetimes for radioactive leakages. With either perspective, there is a belief that health and safety costs in the nuclear power sector are relatively high compared to other methods of power generation and could potentially prove a significant barrier to greater deployment of nuclear power in the UK.

Levelised cost of generation

The screening of all methods of power generation before it is decided if they could be potentially implemented in the UK includes an economic viability assessment – it is only then that options may be considered and their other potential impacts quantified and qualified. Nuclear power needs relatively high provision of capital costs due to the longevity of the planning and construction period of nuclear power stations and also due to the complexity involved in the construction of nuclear power plants and their regulation. One interview stated that if "*The cost of current designs versus safety and environmental detriment could make nuclear uncompetitive".* In addition, decommissioning costs also provide a barrier to nuclear power - the perception of these costs by the public and opponents of nuclear power is that they add an 'unknown quantity' to the true cost of nuclear power, which is provided for by the Government and therefore taxpayer-funded. A stakeholder specific to the nuclear industry stated that "*Decommissioning costs are minor if provided over the lifetime of the technology*" and that "*They (decommissioning costs) can appear to be crippling if unaccounted for until the end of life if the power station*". As a mitigation strategy, one of the stakeholders suggested that "*interaction with regulation and stakeholder perception is key*" (to overcoming these barriers). Although decommissioning costs for the UK's nuclear power plants (most of which are set to begin their decommissioning process over the next ten years) have been estimated, the true cost is not yet known as the full decommissioning process has not yet been carried out in the UK.

Environmental indicators

Land quality and use

Land use and quality is a significant barrier to nuclear power due to the length of time taken to fully decommission land and remediate back to a level where it can be safely used for a wide variety of purposes, and due to the public concern over the contamination and clean-up of the land use. As one of the interviewees consulted stated: "*Plots can be decommissioned to agricultural level, but we need to do this to show the public*".

Contamination of land due to high-level waste burial (within a repository) is also a key public concern with another stakeholder highlighting the lack of long-term strategy for land remediation, asking, "*How do we deal with land being contaminated and the additional land contamination due to waste burial*?"

Radioactive waste production

Radioactive waste production is associated with other impacts, such as human health detriment and environmental (including impacts on biodiversity, land, freshwater and marine environments) impacts and as such, it is high on the public agenda. Its potential effects and the fear of radiation from the public means that radioactivity from nuclear operations are a key societal concern and barrier to expansion of the nuclear power fleet in the UK. A number of the nuclear-specific stakeholders consulted as part of this work believed that radioactive waste has "*very low actual detriment*" and in order to overcome this barrier "*public engagement is key*".

Water use

Nuclear power generation in the UK depends heavily on the use of water for cooling, which is why most nuclear power stations are located at the coast. Estuary water is the most common source of cooling for nuclear power stations, but stations also use freshwater (including lake and river water) and seawater. Coastal locations mean that large amounts of water are readily available in case of emergency cooling. The expansion of the nuclear power fleet would put pressures on demands for cooling water for nuclear power plants – France have already experienced similar problems with droughts and the need for cooling water for their large fleet of nuclear power stations. One stakeholder identified this issue as a future problem for nuclear power in the UK, asking "*France has problems with their nuclear reactors and droughts, will we have the same here?*" The UK is experiencing similar drought-like conditions in the summer months which are trending to more prevalent and extreme occurrences. Therefore, the issue of providing enough cooling water for an expansion of nuclear power stations, or even just maintaining cooling water provision for current power stations could prove a significant barrier to nuclear power in the future.

Social indicators

Nuclear proliferation

In addition to fear of radiation and its impacts and nuclear accidents, nuclear proliferation is also a highly debated and controversial issue surrounding the use of civil nuclear power. One of the biggest arguments for anti-nuclear campaign groups is the spread of nuclear weapons or weapons technology from civil nuclear operations. Although some nuclear experts believe that civil nuclear operations in democratic countries signed up to the Treaty on the Non-Proliferation on Nuclear Weapons can have little influence on the spread of nuclear weapons to volatile states, others believe that by adopting new nuclear in the UK this will increase demand of civil nuclear power in other states and allow the spread of weapons. This divergence in opinion was noted in the stakeholder in interviews. One stakeholder stated that they didn't rate proliferation as a high indicator: "*That genie is already out of the bottle and future non-use of nuclear will not affect this*", but did concede that "*The issue needs to be addressed, however*". Conversely, another interview stated that "*We need to show a lead by not adopting new-nuclear in order for other countries not to follow".*

Human health impacts from radiation

With the fear of radiation high on the public conscience regarding nuclear power operations, the impact of detrimental health impact from radiation leakages is of paramount concern for the public and other stakeholders. Many nuclear industry experts recognise the need to reassure the public and promote the UK's nuclear power sector's safety record with regard to impacts on human health from their operations. This issue is key in achieving positive public perception of nuclear power and it is likely that a relatively severe accident in the UK could potentially leave the Government with no option than to 'kill off' nuclear power in the UK.

Intergenerational equity

The problem of high-level nuclear waste is an expensive and controversial issue which has not yet been solved technically as a waste repository is still to be determined for the UK.

Most of the public and other stakeholders view the continuation of civil nuclear operations in the UK as adding to this problem as more waste will be produced with the next generation of nuclear power stations. The current once-through or open fuel cycle adds to the problem as the waste fuel is currently not used as part of the UK's nuclear power policy (recycling of the fuel reduces waste) and puts pressure on uranium and other resources due to the need for larger amounts of uranium and larger/more waste repositories. However, several of the nuclear-specific experts believed the requirement for radioactive waste management to be minimal, but stakeholder concern over this issue high.

Accident risk

Linked to health impacts and environmental damage from radiation, accident risk is at the forefront of public concern regarding nuclear power operations in the UK. The stakeholders who believed the other related issues to be minimal (associated with the nuclear industry) also identified this issue as relatively minimal, and highlighted the risk assessments for the AP1000 and EPR as evidence of this. New generations of nuclear power plants have a much higher level of safety than past generations, but even with the improvements in safety, public weighting on this issue makes it a huge barrier to expansion and full-acceptance of nuclear power's role in the UK's future energy policy.

Additional identified barriers to nuclear power

High level waste repository

The county of Cumbria has volunteered to be the host county for storage of the UK's high level radioactive waste, but a suitable site is still to be found by the Committee on Radioactive Waste Storage (CoRWM), with several experts disagreeing on the geology of the west side of the county and its suitability, and ultimately safety in hosting long-lived radioactive waste. With no other county having volunteered to take the waste, the uncertainty in the ability to store the waste in the UK's only identified potential host county could prove to be a huge barrier in developing a new generation of nuclear power and the current lack of volunteered site storage for HLW was highlighted as a significant barrier to future nuclear power deployment.

Economic risk

There were two issues highlighted during the stakeholder consultation process which could potentially add to the economic risk associated with investing in nuclear power in the UK. The risk of a nuclear accident anywhere in the world could potentially lead to extremes in negative public opinion of nuclear power and put pressure on the Government to decommission and move away from generation from nuclear fuels (as happened in Germany and Switzerland following the Fukushima disaster in 2011). "*Political sustainability*" of nuclear power policy was highlighted as a particularly sensitive due to risks and perception associated with nuclear power. In addition, the finance risk for nuclear power has been very high due to the economic downturn - carbon prices have not yet been raised to a level which would mean the market for nuclear power is a significantly attractive investment. Moreover, the recession has meant that energy and therefore electricity consumption has decreased, meaning that the UK is currently on target to meet its carbon targets. Therefore, nuclear power again becomes less of an attractive investment as in the short-term; utilities may not be able to make as large a profit from nuclear power generation as other methods due to the decreased need for low carbon electricity.

Sea level rise

The "*sensitivity to sea level*" rise and "*the potential effect on some power stations*" of this was stressed as a significant future sustainability issue for nuclear power. The proximity of many of the UK's nuclear power stations to the coast means that nuclear they are particularly sensitive and vulnerable to future sea level rise. The complexity and cost involved with the construction of nuclear power stations would mean that a sea level rise significant enough to warrant shut down and decommissioning would hinder further development and building of nuclear power stations in the UK.

4.1.3.4.2 Barriers to other electricity-generating technologies

The barriers to other electricity-generating options identified by the expert stakeholders broadly fall into the indicator categories, with barriers within the economic, environmental and social indicators discussed below. In addition to barriers under the indicator headings within the sustainability categories, several additional barriers were also identified and are discussed at the end of this section.

Economic indicators

Fuel costs

Fuels costs for fossil fuel technologies was identified as a barrier to further implementation of these technologies during the consultation process, and it was stated that "*for nuclear, this is not important, for gas, this is very important*". Fuel costs for nuclear power do not have much impact on the total levelised cost of generation as they are relatively low compared to the additional stages of the life cycle. Conversely, fossil fuel prices have much higher importance with fossil fuel technologies, particularly gas-fired power. Fuel costs will have much more impact on carbon capture and storage technologies, which have around a 10% fuel penalty. The future importance of fossil fuels costs on these technologies will depend heavily on economically viable reserves available to the UK. Although carbon capture and storage technologies will initially incur large infrastructure costs, it is likely that the addition of transport and storage infrastructure to the North Sea will lead to enhanced gas recovery. In addition, the shale gas revolution could also mean a new generation of relatively cheap fossil fuel available for UK consumption. However, the future development of coal and gas exploitation is still highly uncertain and a rise in price of these fuels will greatly affect the economic viability of these technologies.

Local economic impacts

Several nuclear sector stakeholders believed that wind power especially would perform badly under this indicator due to the lack of retention of a workforce central to wind farm location. It is widely recognised that centralised power stations that need man-power to be operated are able to retain local community employment more than decentralised methods of power generation, including all renewable technologies. Employment for renewable technologies drops off considerably after the construction phase of the life cycle, due to the lack of fuel needed and minimal maintenance requirements. Therefore, sustainable local community employment is much higher amongst fuelled power stations.

Environmental indicators

Environmental impacts

It was stated several times throughout the expert consultation process that the majority of environmental impacts and detriment were due to the use of fossil fuel technologies. Many of the life cycle environmental impacts of electricity generation are caused by the combustion of fossil fuels, in particular, coal-fired power generation. The most debated impact within the environmental category is global warming potential, of which coal-fired power and gas-fired power have the greatest impact, respectively. The strongest reasons for the discontinuation or minimisation of these fuel sources are the environmental impacts that they cause.

Social indicators

Accident risk

Solar PV and offshore wind technologies were identified as having a high accident risk by stakeholders, due to the nature of both technologies' maintenance and installation processes.

Intergenerational equity

The storage of CO_2 with gas and coal CCS technologies is one of the major drawbacks of CCS and the issue of this storage was addressed during the process of interviewing the expert stakeholders. The CO_2 stored will need to be monitored many generations into the future as leakage could potentially hinder the attempts to limit climate change or cause problems for human health and potentially, fatalities. The intergenerational equity debate surrounding CCS is likely to be one of the most important on the future deployment of these technologies.

Additional identified barriers to other electricity-generating options

National grid

The interviews also highlighted stakeholder concern over decentralised power systems and the national grid. Large-scale implementation of this kind of electricity generation in the UK would require changing the current transmission system. This would be a huge infrastructure project for the UK Government; it would stretch finances, as well as pose a significant problem in terms of planning and public acceptance of new and potentially many more electricity pylons.

Biodiversity

A specific barrier to tidal power was also identified as tidal barrages are well known to potentially have adverse impacts on biodiversity of the aquatic environment in which it is placed in addition to physical changes to the estuary. Because of this, many nations' governments have been reluctant to endorse the development of tidal power, and the projects that have been commissioned have been widely opposed, with many around the world receiving global attention.

4.1.3.4.3 Drivers for nuclear power

The drivers for nuclear power identified by stakeholders broadly fall into the indicator categories, with drivers within the economic, environmental, social and technical indicators discussed below.

Technical indicators

Dispatchability

As stated earlier in the 'barriers to nuclear power' section of this chapter, load following capability of nuclear power was highlighted as a detriment to the technology. However, a spin was put on this by several nuclear specific stakeholders who stated that "*Future nuclear power plants will have a much better load-following capability that present plants*".

Economic indicators

Financial incentives

Nuclear power currently receives a subsidy in the form of avoided CO_2 produced from electricity generation. Although this amount is relatively low compared to renewable technology incentive (nuclear receives £5.08 per MWh electricity produced, compared it total in financial incentives, wind and solar power receive £82.46 and £405.50 per MWh respectively [Stamford and Azapagic, 2012] due to additional subsidies), it was mentioned during one interview that the existing ROC (Renewables Obligation Certificates) incentives for renewables could migrate to other low carbon electricity producing technologies.

Local economic impacts

Nuclear power contributes to substantially employment within the local communities in which power plans operate. Several towns in the UK are built up directly as a result of nuclear power stations. For example, such as Whitehaven in Cumbria (built up from the Calder Hall power station), Oldbury-on-Severn in Gloucestershire (from operation at the Oldbury power station) and Dunbar (from the nearby Torness power station). Several nuclear specific stakeholders advertised the benefits of nuclear power to local economies and communities, stating that "*Employment at a nuclear power station remains at around 800 employees post-construction*". In terms of employment, nuclear power is considered particularly sustainable – in addition to the many people employed during planning, design and construction, employees are retained in the local communities in which power stations operate during operation, and many years after shutdown due to the complex decommissioning process.

Fuel costs

As discussed in the 'barriers to other electricity-electricity generating technologies' section, above, stakeholders identified that total levelised costs for nuclear power are relatively unaffected by rises in fuel costs. This is because fuel costs are low compared to the totalised levelised cost for nuclear power. Fuel costs could also be a potential future driver for nuclear power – recycling of nuclear fuel and use of thorium and plutonium would lower fuel costs and mean that this would have a minimised impact on total levelised cost.

Environment indicators

Environmental impacts

Several stakeholders identified that many of the environmental impacts from electricity generation come from the combustion of fossil fuels. One of the big drivers for nuclear power and its recognised advantage is that (in terms of emissions to the environment) it has a very low environmental footprint.

Lifetime global fuel reserves

One stakeholder interviewed stated that, "*This is unimportant (to nuclear power) provided that we move to thorium and fast reactor technology*". Future fuel cycles and a move to thorium would increase the lifetime of fuel reserves to around 2500 years, therefore making nuclear power significantly more sustainable compared to other fuel-powered electricity generating methods. In addition to this, uranium and other mineral resources have not been fully exploited in terms of identifying economically recoverable reserves as uranium exploration hasn't been carried out much compared to oil, gas and coal exploration.

Social indicators

Fatalities due to large accidents

This issue was also addressed in the 'barriers to nuclear power' section above, and several stakeholders stated that although there is a large fear factor for the public in terms of fatalities from large nuclear accidents, the impact of this over the lifetime of nuclear power is very small.

Security of fuel supply

The ability to stockpile uranium is an important positive factor for nuclear power as uranium is dense in energy and it can also be economically stockpiled due to the relatively low price of uranium compared to the total cost for the nuclear fuel cycle. As one stakeholder identified, "*Cutting supply of uranium supply would still take around one year to* *affect power stations*", whereas the effect from gas cut-off would be immediate.

Accident risk

This indicator was another identified in the 'barriers to nuclear power' section, although several stakeholders believe nuclear plants are built the safer standards today than they used to be, and stated that safety will continue to increase into the future. "*The risk for an accident to occur is currently very small and will continue to decrease*".

4.1.3.4.4 Drivers for other electricity-generating technologies

The drivers for other electricity-generating technologies identified by stakeholders broadly fall into the indicator categories, with drivers within the economic, environmental and social and indicators discussed below.

Economic indicators

Local economic impacts

The potential for wind power to "*fill the energy gap*" created by the timing of closures of large power stations (such as nuclear) was identified as a driver for this technology. The provision of generation to fill this gap is one of the biggest issues surrounding security of supply in the UK. As nuclear power stations take a substantial amount of time to commission, plan and build, this opens up opportunity to other electricity-generation methods to 'fill the gap'. In communities that rely on the local economic impacts, the absence of a large employer will also be gravely felt.

One stakeholder from the solar power sector identified its ability to provide a local economic stimulus as it would need many small-scale projects would be located around the country.

Capital costs and local economic impacts

One stakeholder identified the potential for solar power to contribute to local economies – "*around 50% of the capital costs for solar power are due to installation, which is good for local employment and projects*".

Social indicators

Employment

As stated above, during the consultation process, it was identified that the high employment levels for solar power contribute to its relatively high capital costs, but that this is a benefit in terms of contribution to employment levels. Relatively high employment levels are maintained throughout the lifetime of solar power also due to the high levels of maintenance needed.

4.1.3.5 Systemic issues and challenges

Modelling of complex decisions and systems, such as those surrounding choices on electricity generation encompasses many methodological issues due to the size and complexity of the decision problem being analysed. There is much uncertainty associated with these decisions, due to the timescales involved in the analysis, lack of reliable and up-to-date data, the global influence on UK decision-making and the internal validity of the decision-support model that is being developed. In addition to this, methodological issues associated with the use of sustainability indicators and defining the geographical boundaries of the analysis are also issues which need to be carefully thought through. The stakeholder consultation with many experts who have experience in the modelling of energy systems, or that have been involved with the development of other research in this field allowed identification of the systemic issues associated with modelling a complex energy-decision problem. The coverage in the interviews of each of the types of issues experienced with energy systems modelling includes: spatial issues, scenario validity, external uncertainty, use of relevant indicators and internal uncertainty. The feedback from interviewees on each set of systemic issues is discussed in turn, below.

4.1.3.5.1 Internal uncertainty

Internal uncertainty refers to issues surrounding the development of the assessment methodology framework and the robustness of the measures being used to determine the sustainability of electricity-generating technologies. Internal uncertainty identified from the interviewees involved in the consultation process covered several areas including systems issues and indicator development issues, which are each discussed in turn, below.

In developing a methodology to evaluate the sustainability of an electricity mix of a nation, in addition to comparing individual technologies, the ‘electricity systems factor’ must be taken into account. As one interviewee commented: *“A lot of these parameters are impacted by the system in which they sit. For example, the low load following capability of nuclear energy does not matter provided that it does not dominate the system (and even then, in France they have coped with up to 80% generation, with only a small decrease in capacity factor). Similarly the unreliable nature of wind means not only that the system has to have back up capacity, but this capacity must be capable of running up to generation very fast. In effect, wind commits the system to gas generation or hydro generation”*. The implication of this statement is that the selected electricity mixes, or future technologies must be complemented by technologies which can, in the case of the above example, make up for demand when certain technologies are offline. Electricity-generating technologies may be split into those that provide the base load of electricity, medium load power plants are used when the base load consumption is exceeded, and for peak demand, peak load power plants generate in order to meet these peak fluctuations. Each nation’s power mix is designed with this pattern of electricity demand in mind, therefore future electricity scenarios developed for this analysis must also be constructed based on these assumptions. However, technological innovations of some technologies mean that traditional confinements to base, medium or peak load may not hold-true in the future. Moreover, with increased penetration of renewable technologies as key policy of the UK Government, development of future electricity scenarios must also reflect this, with a clear and careful restructuring of the electricity system as it currently stands. Development of a smart grid will go some way towards solving this problem, as will increased use of storage technologies, such as pumped storage and battery technologies.

The second and final systemic issue discussed in this section covers that of defining the boundaries for the sustainability assessment of electricity technologies and scenarios. Many of the issues discussed and indicators developed are global in nature. For example, global warming potential has no geographical boundaries, although many nations have their own national targets in the reduction of greenhouse gas emissions to adhere to in the global effort to combat climate change. In particular, all of the environmental indicators/impacts are applicable at every stage of the life cycles (from mining/extraction of raw materials to decommissioning of power stations and installations) of the electricity-generating technologies, although most do not have the global impact of GHG emissions.

Although all engineering and economic activities in the UK have an effect globally, the boundary for analysis of many of the indicators has been confined to the UK. The reasoning for this includes: difficulty in assessing economic impacts of buying technologies on a global scale up and down supply chains; decision-making and policy development of the UK Government is often made based on domestic UK economic and social impacts; and other indicators have been designed in order to take into account a localised impact.

Development of economic indicators

Comments and feedback on the validity of the economic indicators that were developed as part of the sustainability assessment indicator framework included the following:

- Gross domestic product (GDP) created from buying foreign technologies, in addition, the GDP of electricity imports and exports would need to be considered.
- Measurement of GDP and employment introduces double counting into the assessment.
- The assessment of fuel price sensitivity is too simplistic to produce meaningful results.

Development of environmental indicators

No comments specifically regarding the validity of the environmental indicators were made during the consultation exercise.

Development of social indicators

Comments and feedback on the validity of the social indicators that were developed as part of the sustainability assessment indicator framework included the following:

- Nuclear proliferation is not normally achieved through diversion from a civil nuclear fuel cycle (i.e. use of plutonium stockpiles). ‘Technical knowledge diffusion’ is more of an issue, for example, Iran acquiring centrifuge technology.
- Storage capacity of fuels should also be taken into account when measuring energy security.

Development of technical indicators

No comments specifically regarding the validity of the technical indicators were made during the consultation exercise.

4.1.3.5.2 Relevant indicator use

Several issues were raised during the interviews that question the relevance and validity of the indicators indicator framework. The issues raised are presented below.

- It should be ensured that there is no double counting with any of the indicators.
- It will be hard to define and obtain data for so many indicators.
- The category definitions of the indicators are artificial as the indicators cross the boundaries of economic, environmental, social and technical impact.
- Measures of corruption and child labour should take into account whether resources come from countries where there are corruption/child labour problems.
- ‘Detriment to investment in renewables’ is a biased indicator and automatically assumes that a high penetration of renewable technologies in the electricity mix is the preferred option.
- Would the economic indicators be effective in assessing conditions in a nationalised versus privatised energy system?
- Many of indicators will not make an impact on the assessment as they will be fairly insignificant – need to do an assessment to see which ones really matter.

4.1.3.5.3 External uncertainty

External uncertainty refers to issues that might affect the assessment of the sustainability of electricity-generating options or scenarios which do not concern the assessment methodology being used. These issues effectively change the decision problem being analysed through uncertainty in the external world. External uncertainty identified from the interviewees involved in the consultation process covered several areas of the developed indicator set in addition to development of future electricity scenarios, which are each discussed in turn, below.

The stability of the prices of the variety of electricity-generating technologies and the fuels that they use is a very uncertain issue that has to be taken into account in the assessment of electricity options and future scenarios. Many different issues can affect this, including: the amount of resources and fuel reserves left in the world in order to operate and build these technologies (this is open to change as there is much uncertainty in the amount of global uranium, for example); the popularity of a certain technology around the world that might lead to faster consumption of reserves and resources; geopolitical sensitivities and the effect that this may have on supply chains and costs; and the market structure nationally and globally for energy/electricity provision would also greatly affect these costs. In addition to the stability of the costs of the technologies, several other indicators were highlighted as particularly sensitive and open to influence from economic and political change including: health and safety fines; accident risk; and lifetime of fuel reserves. In the case of health and safety fines, it was pointed out by one interviewee that fines for breaches in health and safety have evolved enormously over the last 70 years, with changes in technology to higher levels of safety and improved risk assessment. Related to this, accident risk is also another indicator in which the impact could change significantly over time, with improvements in technology bringing about a much smaller risk than current and past technologies. The exploitation of fuel reserves is a much less predictable indicator than those measuring impacts which would be expected to improve with time (such as health and safety fines and large accidents). For example, most crude oil reserves are known about and the currently economical reserves are reaching full exploitation. However, in the case of uranium deposits, it is envisaged that many of the world’s viable and exploitable reserves are still not known about, as uranium exploration hasn’t been carried out to the same extent as many other resources. Therefore, discovery of large uranium deposits would mean that a current assessment of the lifetime of fuel reserves based on current knowledge is invalid. Moreover, fuel reserve lifetime is sensitive to demand globally for various fuels and this also affects the costs indicators. For example, low demand for natural gas globally would mean lower prices and higher availability in the UK. Therefore, the future electricity scenarios developed as part of this project would need to take into account caveats such as this that may arise from how energy policy develops globally.

In relation to the development and assessment of future electricity scenarios, the percentage penetration and the amount of electricity supplied by the variety of technologies available will need to be analysed from a 'systems' perspective, in order to determine the effect that having a relatively high, or low penetration of a certain technology may have on the whole system. For example, a high penetration of wind power might mean that much of the remainder of the electricity mix would need to be relatively flexible in order to meet peak electricity demand when power from wind farms in unavailable. Related to this, it was pointed out by one interviewee that the future price of gas would have a big impact on which technologies would be more attractive for the Government to pursue. A low gas price and/or a higher availability of gas to the UK would obviously mean that the UK Government would pursue a 'dash for gas'-type energy policy, which is currently being undertaken by the Coalition Government as was announced in the recent Energy Bill (DECC, 2012a). Gas-fired power stations often make-up the shortfall in electricity supply when not enough wind-power is being produced. A higher penetration and lower price of gas could mean that the demand to build a higher quantity of nuclear and coal-fired power stations (with and without CCS) is reduced somewhat.

Another point made on the assessment of future electricity scenarios highlighted the probability that several indicators under specific scenarios would have the most impact and therefore 'dominate' the sustainability assessment. For example, a high penetration of carbon-intensive technologies within a particular scenario would mean that the greenhouse gas emissions impact would become one of the main sustainability issues associated with such a scenario. It was therefore suggested that in order to simplify the assessment of the scenarios, the 'main' impacts should be analysed in more detail by assessing the error margin on their impacts in order to understand how sensitive a particular scenario is to changes in impact of some indicators. Therefore, caveats could then be placed on certain indicators to determine whether a scenario would be viable or not. In addition, it was also suggested that the risk of pursuing certain energy policies, such as a large fleet of nuclear power stations at a time of public uncertainty or disapproval of the technology, or in case of a large accident should be investigated. For example, the economic implications of this could be estimated.

4.1.3.5.4 Validity of scenarios

That the developed scenarios should be implementable in terms of economic, technical and political viability was another major issue that was highlighted by several stakeholders during the expert consultation process. Several issues identified that would need to be addressed in order to determine viability include the following:

- How much private investment and/or Government funding would be needed in order to finance different UK electricity mixes?
- Would supply chains be capable of providing services, components and products needed in order to build the variety of electricity mixes?
- The timing of building new capacity needs to be thought about, for example, large infrastructure projects such as the building of a fleet of new nuclear power stations, in conjunction with other nationally significant projects (such as construction associated with the Olympics and development of the Thames Barrier) would put a large strain on human and supply chain resources.
- The chosen electricity mixes should be technically viable and penetration of various technologies should be complementary to other technologies included with the mix (for example, wind power should be matched by a technology or technologies that can provide quick ramp-up in times of low availability).

4.1.3.5.5 Spatial issues

Several stakeholders highlighted that the impacts being measured as part of the methodology did not take into account the effect that certain issues would have geographically. For example, many of the life cycle environmental issues measured will ultimately have impacts dispersed and concentrated at certain points spatially, depending on the pollutant, its transfer pathway, medium and sink. The life cycle assessment methodology employed in this methodology gives ‘potential’ impacts for a range of environmental categories. Specific modelling of pollutant-pathway-impact modelling is beyond the scope of this project due to the number of processes involved with the complete life cycle of the many different electricity-generating technologies assessed as part of this project. However, several stakeholders believed that the actual impact of the environmental issues were important to determine, in addition to the local versus national impact of some of the social issues (local economic impacts as well as radiation intensity at different locations) and that biodiversity impacts was also an important impact to measure.

4.1.4 Summary of the first-stage expert consultation

On average, the results from the quantitative survey showed that the stakeholders thought that the indicators were important in assessing the sustainability of nuclear power compared to fossil fuels and renewables (the average rating overall was 2.9) and the technical indicators were considered the most important when assessing the sustainability of energy technologies, followed by environmental, then social and finally, economic.

The indicators with the highest average ratings were: lifetime of global fuel reserves at current extraction rates; GHG emissions; radioactive waste production; total production costs; fatalities due to large accidents; active waste management required for future generations; and security of fuel supply (all with an average score of over 3.5). The only indicator that received a score of less than 2.0 was: percentage of sites with ‘fly-in, fly-out’ operations.

These findings show that the perspectives of different stakeholder groups differ with regard to some of the sustainability indicators. The reasons for the differences and perceptions may be complex and not simply a result of the organisation that they represent, although it can be assumed that the perception of the value of the sustainability indicators will, on average, vary between stakeholder groups.

In addition, as identified in the results analysis of this section, the stakeholder sample is biased towards academic experts and the sample size is relatively small. Therefore, more research is needed to be carried out on the difference of opinion between different stakeholder groups in order to confirm or contradict these findings. Although the results do display some statistical significance between groups, this could change if the number of responses from the questionnaire increased. Further dissemination of the questionnaire or further expert consultation to the relevant stakeholder groups will allow the findings of this initial consultation to be validated or disproved.

This chapter on the first stage of expert stakeholder consultation has identified the main stakeholder concerns with regard to implementation of a new nuclear power programme in the UK. Expert feedback on the first draft of the SPRIng sustainability indicators was sought and used in order to further develop and improve this set of indicators. Qualitative and quantitative feedback from the first stage consultation interviews allowed identification of: the expert stakeholder perceived important and unimportant issues; the drivers and barriers to nuclear power and other electricity-generating options in the UK; additional issues and indicators that had not been included as part of the SPRIng indicator framework; stakeholder requirements of the decision-support framework; and systemic issues that should be considered as part of the development of a decision-support methodology.

The expert stakeholder interviews were carried out in order to develop an improved method for robust decision-making on energy policy. In addition, the consultation process with a series of experts is critical for the improvement of knowledge and access to data for the modelling of energy systems and maintaining stakeholder relations and managing expectations is crucial for effective deployment the developed tool / method.

The next section presents the results of the second stage of expert consultation.

4.2 Stage 2 Expert Stakeholder Consultation: Multi-Criteria Perspectives on Electricity Generation in the UK

4.2.1 Aims and objectives of the multi-criteria expert questionnaire

The aim of this stage of the consultation process was to use the final set of the sustainability indicators and find out how the expert stakeholders rate the importance of different indicators. Preference weighting has been used for these purposes. The derived weights are not only nuclear-focussed - but take into account all significant electricity-generating options in the UK. In this way, nuclear power can be modelled against all other electricity options in order to determine the ‘most sustainable’ option, or options under the expert weighting. In addition, expert preferences on the importance of the sustainability impacts of electricity-generating technologies are also sought, so that the multi-criteria decision model takes a slightly more objective angle (due to the ‘bounded rationality’ of experts in different fields who may not always understand or are aware of the impacts arising from operation of other electricity-generating options). The specific objectives of the expert multi-criteria consultation were:

- to determine expert stakeholder opinion on electricity-generating options in the UK;
- to identify the most controversial electricity options and sustainability issues;
- to identify which electricity options and sustainability issues generate the most consensus from stakeholders;
- to generate MCDA weights for the expert stakeholder group in order to feed into the electricity scenario assessment in chapter 8 of this thesis.

Further detail on the research methodology used in the expert survey exercise can be found in section 4.2.2. Section 4.2.3 details the findings from the expert survey exercise and section 4.2.4 discusses these results and concludes the finding from the expert MCDA survey.

4.2.2 Stage 2 research methodology

Part of this consultation exercise has sought to determine expert opinion and preference weights for the indicator framework developed by Stamford (2012), in addition to opinion and preference weights on electricity-generating options in the UK. The list of indicators in the second phase of expert engagement was reduced to 43 indicators (some indicators were removed or amended following the first phase of expert consultation). A description of each of the indicators was provided within the survey so that each stakeholder could understand as many of the indicators as possible.

4.2.2.1 Expert stakeholder sample

A wider sample of experts was sought to take part in this survey than the first expert survey in order for gauge the opinion of as many nuclear and electricity-sector experts as possible. Sampling was carried out online as the survey was in electronic format in the Qualtrics survey software (www.qualtrics.com). Experts that took part in the first stage of the consultation were asked if they would be willing to take part in the questionnaire. In addition to this, The National Nuclear Skills Academy also agreed to advertise the survey on their Facebook, Twitter and LinkedIn websites and as well as within their newsletter. Emails were also sent out to experts in the SPRIng partners group, and many other energy research groups across the UK. Sampling for the survey took place between July and September, 2011.

In total, 45 individuals took part in the expert MCDA survey.

Descriptions of technical issues were produced for the respondents to clarify and explain technical or scientific terms for both surveys. The descriptions (Appendix 4 Description of Sustainability Indicators for Expert Survey 2) gave descriptions of each of the indicators that were asked to be considered as part of the survey. As with the Stage 1 consultation, the idea was to put all stakeholders consulted on an ‘equal footing’ before carrying out the survey. The main aim of this was to minimise any bias in knowledge of the issues, so that the feedback on the indicator framework would come from individuals who shared the same level of information on the indicators as each other.

4.2.2.2 Development of expert questionnaire 2 : MCDA survey

The expert MCDA questionnaire (Appendix 3 Expert Multi-Criteria Perspectives Survey) included one Likert-style question seeking to assess how favourable each individual believed each electricity-generating option to be. The remainder of the questions within the survey were aimed at eliciting weights for:

- electricity-generating options (by using a simple rank-style question);
- each of the indicators (by using a simple multi-attribute value technique); and

- weights for each of the sustainability aspects – techno-economic, environmental and social (derived using the AHP technique – see section 2.4.3 for a description of this methods).

The choice of MCDA method was largely dependent on the number of criteria being compared in each stage of the assessment (for example, pairwise comparisons cannot be made across many criteria as the number of comparisons rises exponentially with increasing criteria).

In addition to the above questions, the experts were also asked for feedback on several more issues, evaluated below:

1) Any additional issues that they believed were important to consider.
2) Why the additional issue(s) (if any were specified) were believed important to consider.
3) If there was any other feedback, comments or information regarding electricity generation in the UK.

4.2.2.2.1 Data collection

Samples were collected in the form of an online questionnaire using the Qualtrics survey software (www.qualtrics.com) A total of 45 questionnaires were fully completed between July and September 2011. Of the surveys completed, six respondents (13.3%) had previously participated in the first stage consultation.

4.2.3 Questionnaire survey findings

4.2.3.1 Survey demographic

Of the 45 questionnaires completed, males accounted for 91.1% of the responses (41 counts) and females 8.9% of the responses (four counts). The stakeholders were classified into different stakeholder groups to determine if there was any disparity in responses between stakeholders groups. These groups are: academia (31.1% of responses), energy supply industry (17.8% of responses), government agency (8.9% of responses), consultant

(15.6% of responses), NGO (6.7% of responses), association (0% of responses), regulator (0%), politician (0% of responses) and other (20% of responses). The contributions of which can be seen in Figure 4.5.

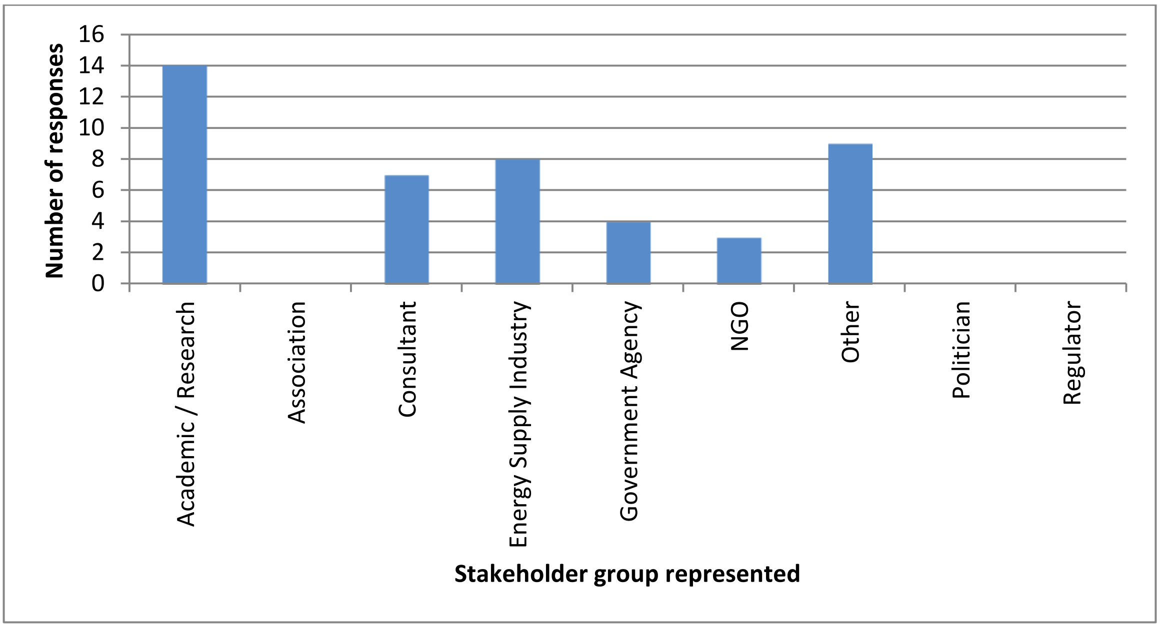


Figure 4.5. Stakeholder group demographics by organisation type.

Of those working specifically in the electricity supply industry, fifteen worked in the nuclear industry, four in the renewable energy industry, and two as part of an environmental pressure group, six in multiple industries and eighteen respondents worked in none of the above industries (see Figure 4.6).

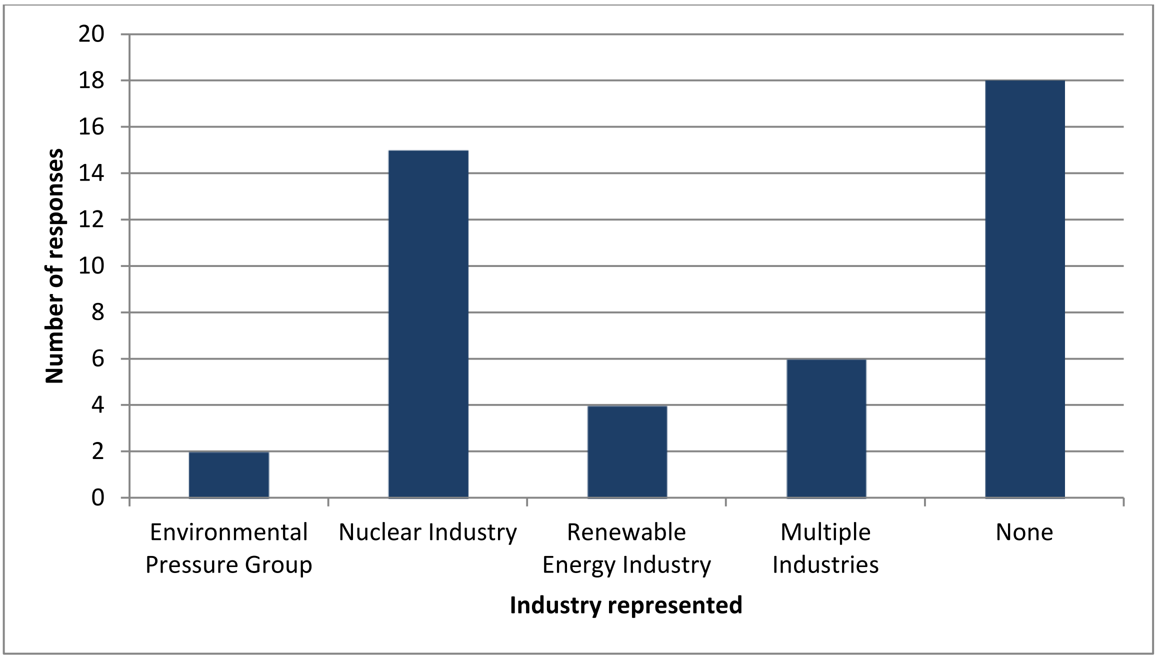


Figure 4.6. Stakeholder group demographics by industry represented.

4.2.3.2 Survey results

4.2.3.2.1 <u>Expert stakeholder perceptions of electricity-generating options</u>

The perceptions of electricity-generating options were considered by respondents of the survey in isolation of the quantified potential impacts. Hydroelectric power was found to be the most favourable electricity-generating option amongst the sampled experts (with 87% favourable towards this source), followed by solar power (73% favourable), nuclear power (71% favourable), wind power (60% favourable), biomass-fired power (58% favourable), coal- and gas-fired power equally favourable (20%) and finally, oil-fired power (4% favourable). The results are displayed in Figure 4.7.

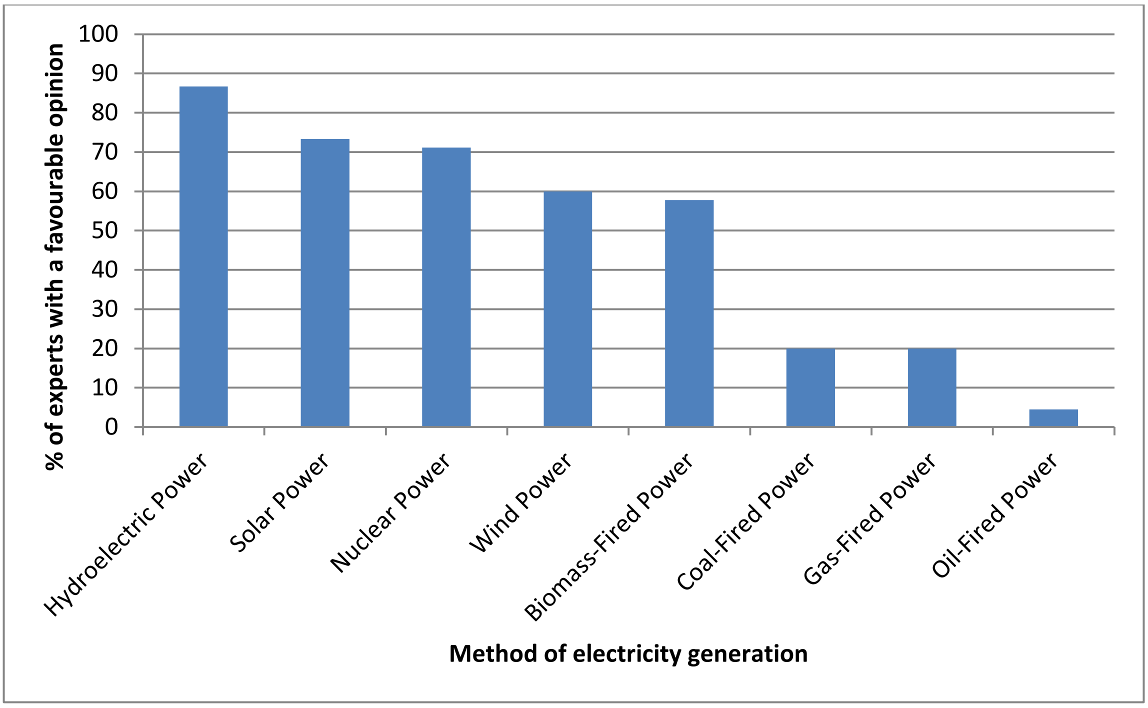


Figure 4.7. Expert favourable opinion on electricity-generating technologies in the UK.

Unfavourable expert opinions on electricity-generating options for the UK are represented in Figure 4.8, below. Generally, the graph is an inverse of the favourable opinions graph displayed above, although in the case of the unfavourable opinion on coal- and gas-fired power, these technologies are not considered equally unfavourable (coal-fired power is considered more unfavourable than gas-fired power). Oil-fired power was considered the most unfavourable method by which to generate electricity, with 78% of experts rating it as unfavourable. Coal-fired power followed at 56% unfavourable, and gas-fired power was rated 49% unfavourable. Technologies rate as significantly less unfavourable were: biomass-fired and wind power (both 18% unfavourable); solar power (7% unfavourable) and hydroelectric power (4% unfavourable).

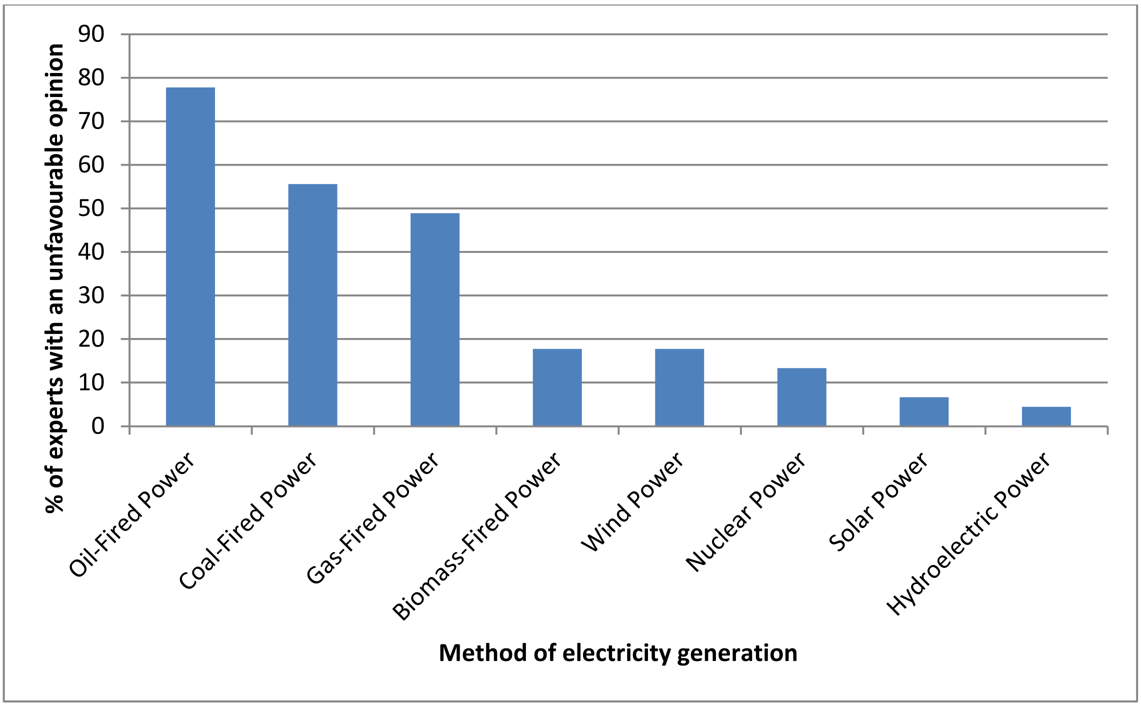


Figure 4.8. Expert unfavourable opinion on electricity-generating technologies in the UK.

The balance in opinion on nuclear power is very biased towards nuclear, with 71% of respondents believing nuclear power favourable and only 13% believing that it is unfavourable. As the stakeholder sample contained a relatively large proportion of experts from the nuclear industry (33.3%), the bias in favourability towards nuclear power is likely to be due to the sample bias.

4.2.3.2.2 Multi-criteria perspectives on electricity-generating technologies

The MCDA ranking of electricity options was also carried out by the expert stakeholders before the impacts of electricity generation (the sustainability indicators) were weighted. The stakeholders were asked to carry out a simple ranking of the options presented to them (in alphabetical order: biomass-fired power, coal-fired power, gas-fired power, hydroelectric power, nuclear power, oil-fired power, solar power and wind power) and were also given the option of specifying an additional or alternative form of electricity generation that was not included in the assessment. Each stakeholder ranked the eight electricity options (or nine, if an extra option was suggested) in order of their preference for electricity generation in the UK, with ‘1’ as the best/most favourable option, and ‘8’ or ‘9’ as the worst or least favourable option.

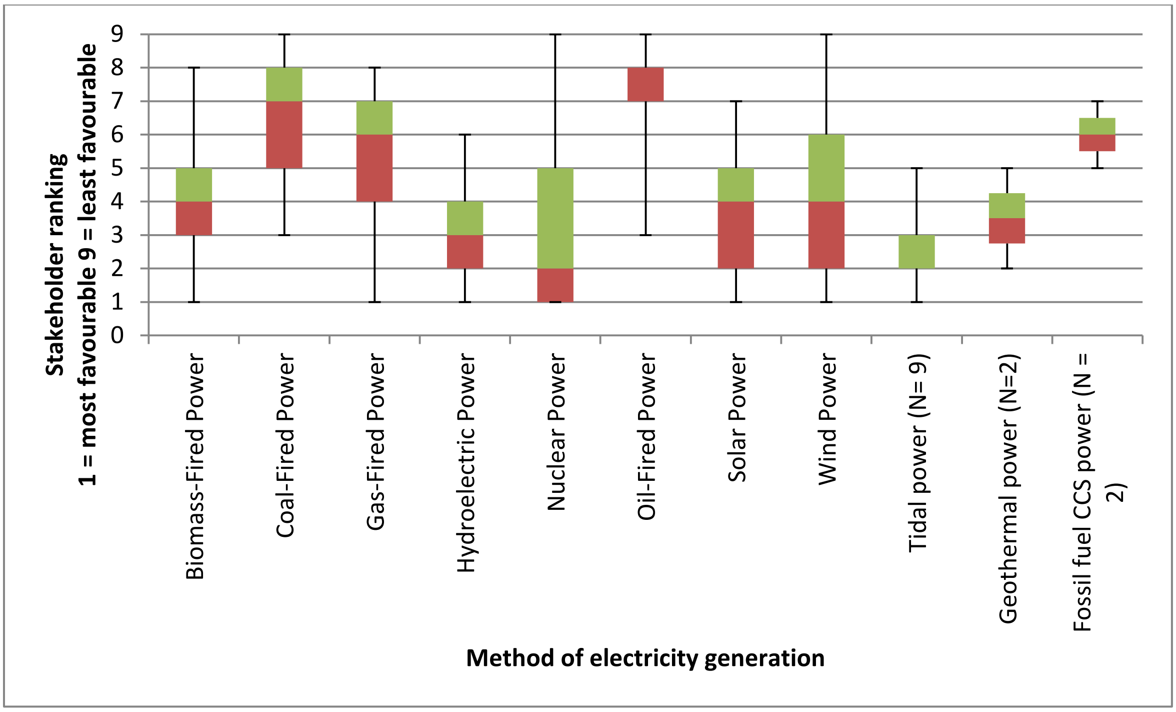


Figure 4.9. Boxplot displaying the distribution of stakeholder rankings for UK electricity options. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

The range of stakeholder rankings for each electricity-generating option are displayed in Figure 4.9. For the additional suggested electricity-generation methods, the number of experts that rated each additional method is noted in brackets on the graph. The boxplot of the distribution of stakeholder rankings displays the lower quartile, the upper quartile and the 25th, 50th and 75th percentiles. The green and red boxes meet at the median value, and each represent the second and third quartiles of the data. A wider box indicates a wide spread of data. The error bars represent the minimum and maximum values. Amongst the eight electricity generation methods rated by all stakeholders, most consensus was reached on the rating of oil-fired power as unfavourable. Coal- and then gas-fired power as the next least preferred option, although the boxplot displays a wider rating and therefore split in opinion of these technologies compared to oil-fired power. Biomass, solar and wind power all display the same median values in ranking; biomass-fired power has a smaller distribution of data around the mean however, meaning that it is the most preferred option out of those three, this is followed by solar and then wind power. Hydroelectric power is the second most preferred option, and nuclear power is the most preferred option out of the eight technologies ranked by all stakeholders. Three additional technologies were suggested by stakeholders and included: tidal power (suggested by nine stakeholders);

geothermal power (suggested by two stakeholders); and fossil fuel CCS power (suggested by two stakeholders). Out of the three suggested technologies, tidal power was ranked the best, followed by geothermal and then fossil fuel CCS power. As the sample sizes for these technologies are small, their rankings are relatively unreliable, but do give an indication of alternative power generation methods being considered by experts in the field of electricity generation.

4.2.3.2.3 Multi-criteria perspectives on the SPRIng sustainability indicators

The MCDA ranking of the 43 sustainability indicators was also carried out by the expert stakeholders. The stakeholders were asked to carry out a simple multi-attribute value theory ranking of the options presented to them in order of sustainability aspect, starting with techno-economic indicators, then environmental and finally social indicators. Each stakeholder rated the 43 indicators in order of importance within the indicator groups. Stakeholders were asked to specify the relative importance of each indicator, by assuming a hypothetical scale of 0-100 and first beginning by assigning the most important indicator a score of 100. They were then asked to then assign each subsequent indicator to a position on the scale (0-100) that they thought represented its relative importance in relation to all the other indicators. They were also asked to assign indicators that were considered equally important the same value and to assign the least important indicator a score of 0.

4.2.3.2.4 Total sample results

A boxplot of the total sample results for all of the stakeholder rated sustainability indicators can be seen in Figure 4.10 and Figure 4.11. The indicators are arranged in terms of importance within their impact groups, starting with techno-economic and environmental indicators, and finally, social indicators. The techno-economic indicators display the highest average median (50th percentile) rating at 62.8, followed by social indicators at 60.4 and finally, environmental at 56.4. Across all of the indicators, most consensus was reached on the importance of global warming potential, with the majority of stakeholders agreeing that global warming potential is one of the most important issues to consider in a sustainability assessment of electricity-generating technologies. In addition, relatively high agreement was reached on technical dispatchability and operation and maintenance costs. Overall, the techno-economic indicators display the most consensus and the least distribution, followed by the social indicators, and then the environmental indicators, which proved to be the most controversial measures, on average, amongst stakeholders. The most controversial issues were material recyclability, human health impacts from radiation (total), radioactive waste to be stored and total employment.

Figure 4.10. Distribution of expert stakeholder rankings for the techno-economic and environmental indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

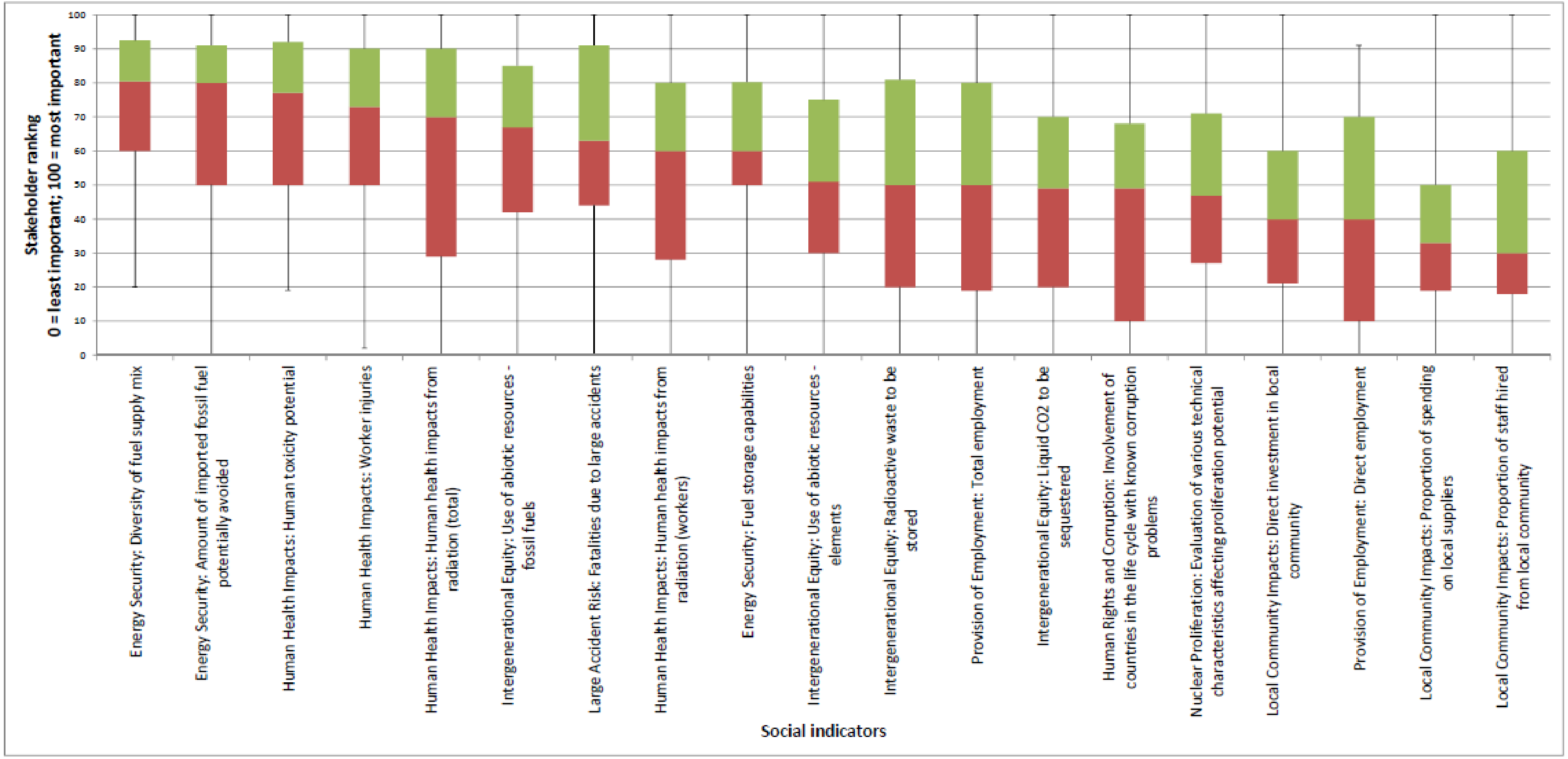


Figure 4.11. Distribution of expert stakeholder rankings for the social indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

4.2.3.2.5 Techno-economic sustainability indicators

The techno-economic group were rated first, and consisted of 13 indicators. A boxplot of the results for the ratings of the techno-economic indicators can be seen in Figure 4.12 which are displayed in the order of presentation in the survey. The most important techno-economic indicator is considered to be lifetime of global fuel reserves, followed by total production costs and availability factor. The least important techno-economic indicators were considered to be time to plant start-up, financial incentives and assistance and capital costs.

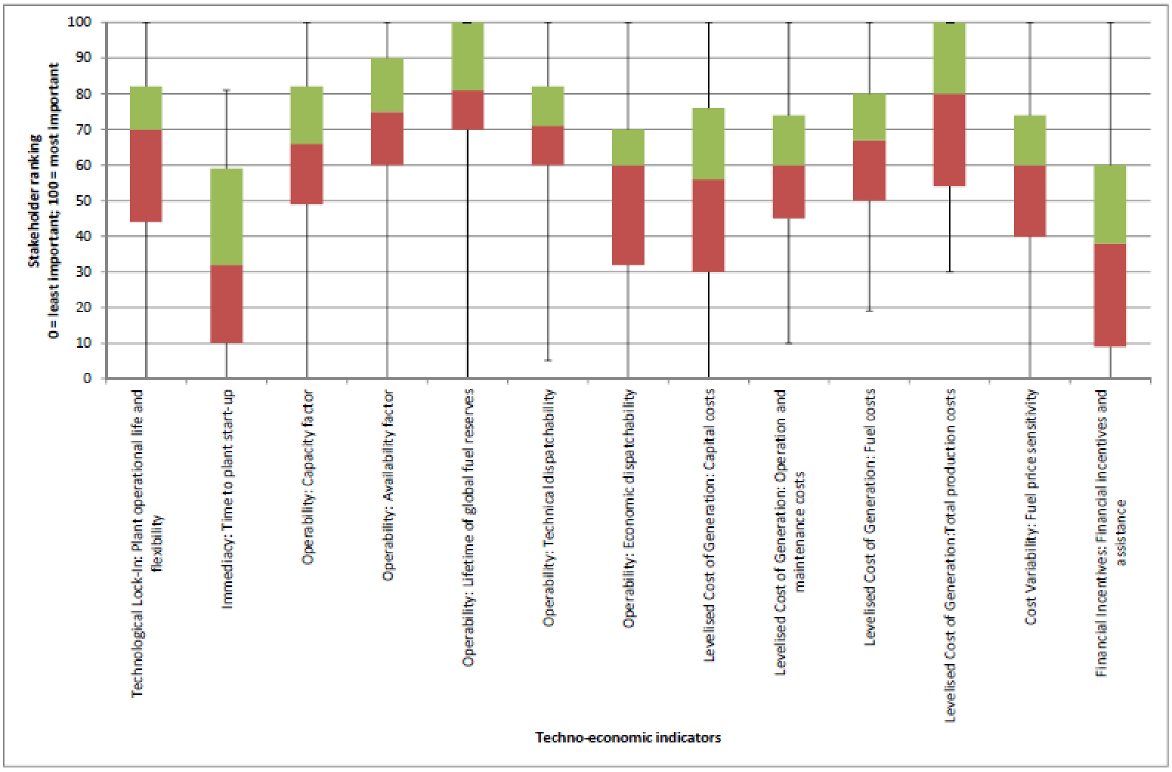


Figure 4.12. Boxplot displaying the distribution of stakeholder rankings for the techno-economic sustainability indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

Across all of the indicators, most consensus was reached on the importance of technical dispatchability, followed by operation and maintenance costs. In addition, relatively high agreement was reached on technical dispatchability and operation and maintenance costs. The most controversial issues amongst the techno-economic indicators were: financial incentives and assistance; time to plant start-up; capital costs; and total production costs which all displayed the widest distribution in ratings.

4.2.3.2.6 Environmental indicators

The environmental group of indicators were the second group of indicators to be rated, and consisted of 11 indicators altogether. A boxplot of the results for the ratings of the environmental indicators can be seen in Figure 4.13 which are displayed in the order of presentation in the survey. The most important environmental indicator is considered to be global warming potential, followed by freshwater eco-toxicity and photochemical smog creation potential. The least important environmental indicators were considered to be land occupation, greenfield land use and eutrophication potential.

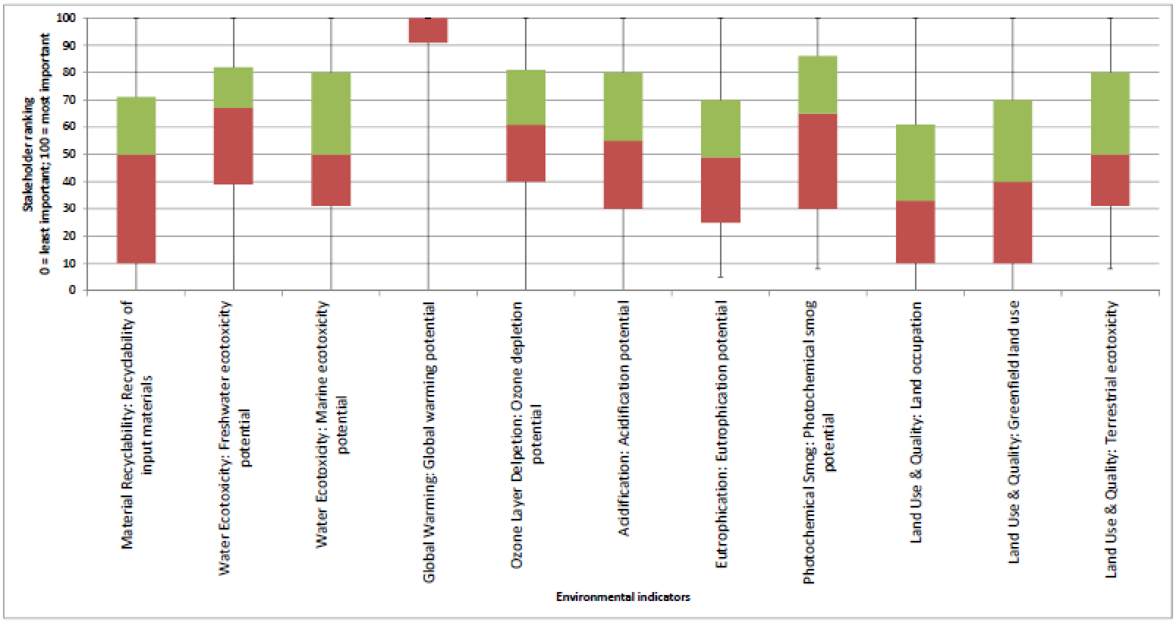


Figure 4.13. Boxplot displaying the distribution of stakeholder rankings for the environmental sustainability indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

Across all of the indicators, most consensus was reached on the importance of global warming potential, followed by ozone layer depletion potential and also freshwater eco-toxicity potential. The most controversial issues amongst the environmental indicators were: recyclability of input materials; greenfield land use; and photochemical smog creation potential which all displayed the widest distribution in ratings.

4.2.3.2.7 Social indicators

The social set of indicators was the final group of indicators to be rated, and consisted of 19 indicators altogether. A boxplot of the results for the ratings of the social indicators can be seen in Figure 4.14. The indicators are displayed in the order of presentation in the survey. The most important social indicator is considered to be diversity of fuel supply mix, followed by amount if imported fossil fuel potentially avoided and human toxicity potential. The least important techno-economic indicators were considered to be proportion of staff hired from the local community, proportion of spending on local suppliers and direct employment. Across all of the social indicators, most consensus was reached on the importance of fuel storage capabilities, proportion of spending on local suppliers and diversity of fuel supply mix. The most controversial issues amongst the social indicators were: human health impacts from radiation (total); radioactive waste to be stored; and total employment which all displayed the widest distribution in ratings.

Figure 4.14. Boxplot displaying the distribution of stakeholder rankings for the social sustainability indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

4.2.3.2.8 Multi-criteria perspectives on the sustainability aspects

Clustering analysis was carried out on stakeholder opinions on the importance of the sustainability indicators and the results of this are displayed in the ternary diagram in Figure 4.15, plotted using the Microsoft Excel tri-plot (Graham and Midgley, 2000). The values for the clustering analysis were calculated for each stakeholder by determining the average (mean) rating that each respondent gave to the techno-economic, environmental and social aspects of sustainability, based on ratings from the groups of indicators. The average scores were then normalised and the percentage leaning towards each of the three pillars of sustainability was calculated for each stakeholder.

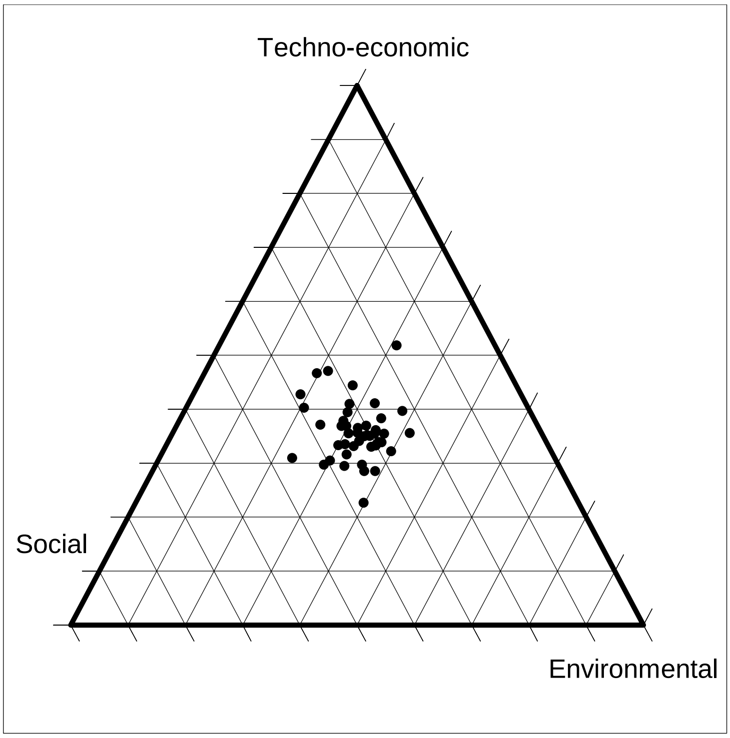


Figure 4.15. Distribution of stakeholder ratings for the three pillars of sustainability generated from average indicator ratings.

This analysis has been carried out in order to determine if any of the stakeholders seemed to form ‘groups’, based on their average ratings of each set of sustainability indicators. Averaging the indicators over each aspect of sustainability tends to give central values across the three groups, largely because respondents found some indicators within each group very important, whilst others were rated as much less important. However, the mean values show that there is a slight tendency towards the techno-economic indicators, slightly less tendency towards the environmental indicators and least tendency towards the social indicators. This is indicated through the most dense clustering area on the ternary diagram with a leaning of around 37% for techno-economic, 34% for environmental and 31% for social preferences. In addition, there are more outliers leaning towards techno-economic sustainability than towards social and environmental sustainability. The results from the distribution analysis in the boxplots also supports this. However, the difference is relatively small and should be interpreted with the small sample in mind.

Clustering analysis was also carried out on the AHP weights (for information on this MCDA method see section 2.4) which were derived from the expert survey. Each respondent was asked which pillar of sustainability they considered to be the most important through use of the analytical hierarchy process. Pairwise comparisons were made across each of the pairs of sustainability indicators (environment compared to social, social compared to techno-economic and environmental compared to techno-economic) and respondents specified the extent to which one aspect was preferred above the other on an ordinal scale of 1-9 (1 = equally important; 3 = slightly more important; 5 = strongly more important; 7 = very strongly more important; 9 = extremely more important; and values of 2, 4, 6 and 8 are used where compromise was needed). The eigenvectors were then calculated for each stakeholder's ratings for each sustainability aspect (this is done by multiplication of each of the entries from a single stakeholder and then taking the n^{th} root of the product – the n^{th} roots for each comparison are then summed which allows normalisation of the eigenvector values). The percentage leaning towards each sustainability aspect was then calculated to feed into the tri-plot spread sheet. The results from these calculations can be seen in Figure 4.16. In addition, the AHP values can be viewed in Appendix 5 AHP Weighting Results of the Sustainability Aspects from the Second Stage Expert Questionnaire.

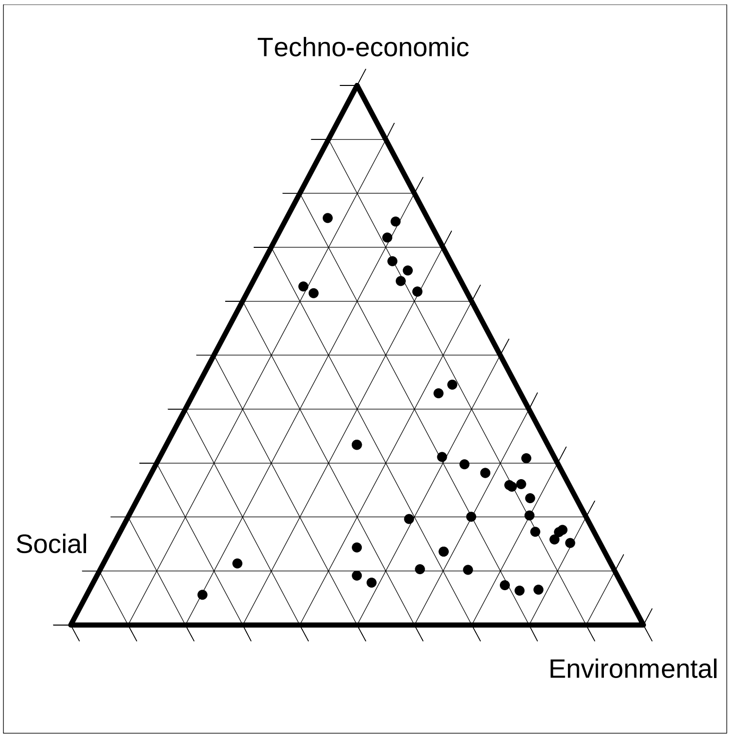


Figure 4.16. Distribution of stakeholder weights for the three pillars of sustainability based on AHP values.

From the ternary diagram displaying the range of AHP stakeholder preference for the importance of the sustainability impacts, it can be observed that the distribution of preference is much greater than those calculated from the average stakeholder ratings for the sustainability indicators. The majority of the results are plotted with an emphasis on environmental importance (leaning of 48%), with techno-economic second in overall importance (31%) and lastly, social sustainability viewed as the most important aspect by only two stakeholders (leaning of 21%). These results are in sharp contrast to the average rating of the indicators displayed in Figure 4.15. It is interesting to note the disparity in individuals' views in rating of the sustainability aspects (i.e. techno-economic, environmental and social) compared to the average rating of the individual indicators (displayed in Figure 4.15).

4.2.4 Summary of the second stage of expert consultation

The results from the second-stage MCDA survey showed that the stakeholders thought that hydroelectric power was the most favourable electricity option operating in the UK today, followed by solar and then nuclear power. The most unfavourable options were considered to be oil-, coal- and gas-fired power. However, the most controversial options amongst stakeholders with least agreement on their favourability were coal- and gas-fired power in addition to nuclear power. Most agreement was reached on the disapproval of oil-fired power and the approval ratings of biomass-fired power and hydroelectric power.

Overall, the techno-economic indicators were rated as the most important indicators and had the highest average rating, followed by the environmental indicators and, on average, the social indicators were considered the least important. Most stakeholders agreed that global warming potential was a very important issue. In addition, stakeholders displayed relative agreement on the importance of technical dispatchability and operation and maintenance costs. The least controversial set of indicators was the techno-economic set, which displayed least distribution and the most controversial set was the environmental set of indicators. This analysis allows identification of particularly contentious issues where decision makers and influential stakeholders would not be able to reach a consensus in taking decisions on nuclear power and the future of the UK’s electricity mix. In addition, the indicators where consensus is reached and there is likely to be agreement on importance are also identified.

The second stage of expert stakeholder consultation has identified the main stakeholder concerns with regard to implementation of a new nuclear power programme in the UK. The MCDA preferences and weights can be used to determine how stakeholder opinion could influence UK electricity and nuclear power policy in the UK. This research is followed up in Chapter 8, where future electricity scenarios are modelled using a variety of stakeholder perspectives in order to explore how expert decisions can affect decisions made on energy policy.

Prior to that, the next chapter details the findings from the public consultation process.

5 Stakeholder Perspectives on the Issues Surrounding Electricity Generation: Public consultations

Recent policy debates surrounding decisions on the future UK electricity-mix are often centred on climate change mitigation and energy security. Consequently, many surveys on the public opinion of electricity-generating technologies have focussed on these variables in relation to electricity-generating technologies. For the first time, a comprehensive set of sustainability indicators (developed in order to measure and compare the sustainability of nuclear power in relation to electricity-generating options) have been presented to a sample of the UK public. The survey has been carried out in order to determine how important the UK public believe these issues to be in addition to determining opinion on electricity-generation methods. Moreover, decisions on the future of nuclear power in the UK must be made on an integrated basis – taking into account the full electricity mix, using a number of relevant sustainability criteria and with the input of key decision-makers, expert stakeholders and the public.

5.1 Aims and Objectives of the First Public Questionnaire

With the above in mind, the overall aim of this public consultation process was to identify what the public believe are the main issues associated with the sustainability assessment of electricity-generating technologies in the UK (focussing on the three tiers of sustainability – techno-economic, environmental and social impacts). The survey is not specifically nuclear-focussed and takes into account all significant electricity-generating options in the UK. The rationale for this is that in order to determine public opinion on nuclear power, these opinions should be in relation to opinions on other technologies in order to aid comparison to similar surveys and also to allow nuclear power to be evaluated in an integrated electricity mix. The specific objectives of the public consultation include:

- to engage with as many members of the public as possible in order to gauge as unbiased a response as possible in the given time frame;

- to identify which electricity-generation methods the public would want to increase penetration of, and which electricity-generation methods the public would want to decrease penetration of;

- to identify which sustainability indicators are believed to be of highest value in assessing the sustainability of electricity-generating options amongst the public;

- to identify which sustainability indicators (if any) are believed to be of little value in assessing the sustainability of electricity-generating options amongst the public;

- to identify current public opinion on electricity-generating technologies and determine if there is any correlation between preferred electricity options and the importance of the sustainability issues outlined.

In addition to the above objectives, an additional objective was identified in the wake of the Fukushima disaster of Japan – survey sampling began before the disaster and continued during the disaster and into the aftermath of the events surrounding the Fukushima Daiichi nuclear power plant. Therefore, the results from this survey will allow determination of a another objective – identification of whether the events in Japan affected UK public opinion on nuclear power operations in the UK.

Further detail on the research methodology used in the public survey exercise are discussed in the next section. Section 5.1.2 details the findings from the public survey exercise and section 5.1.3 discusses these results and summarises the finding from the public survey.

5.1.1 Stage 1 research methodology

The consultation exercise has sought to determine public opinion on the indicator framework developed as part of the SPRIng project (Stamford and Azapagic, 2012), in addition to opinion on electricity-generating options in the UK. The initial indicator framework presented to the public was presented as economic, environmental social and technical aspects (the final set comprises three sets of indicators, with techno-economic measures being compounded into one set). The indicators presented to the public were simplified in order to aid understanding of the sustainability issues surrounding electricity generation in recognition that some members of the public may have never heard of some of the issues that had been identified. Findings from the first expert stakeholder survey were used to feed in to this – the top fifteen most important indicators identified by experts were used in order to gauge public opinion on these indicators. The list of indicators can be found in Appendix 6 Public Engagement Survey 1.

5.1.1.1 Theoretical frameworks

Public participation in policy decision-making and influence on government decision is a feature of all democratic nations. Democratic theorists propose that the public are influential in governmental policy decision-making and policy implementation (Walker, 1966). Therefore, it is usual that governments recognise and take on board public opinion when framing (in this case), energy policy, or more specifically, policy regarding the implementation of a new generation of nuclear power stations in the UK. It is with this theory in mind that the public opinion surrounding electricity generation and the potential sustainability impacts is measured. The prediction of the responsiveness of the government to public opinion in decision-making on nuclear power is beyond the scope of this thesis – there is no theoretical framework (as far as the author of this thesis is aware) that allows the prediction of government policy decision-making on this basis. However, the finding from this survey will allow identification of public support for, and opposition to the variety of electricity-generating technologies, in addition to identification of the public opinion on the importance of the range of impacts of electricity generation. This information is useful to government and decision-makers in determining: which electricity-generating technologies prove to be the most controversial amongst the public and are the most sensitive to mass-public opposition, and; which sustainability impacts the public sees as the most important (and therefore on which impacts the government should take action). Once again, as with the expert consultations, a coevolutionary approach is taken in gauging public opinion on nuclear and other electricity-generating technologies. This is in recognition of the need to gauge opinion on all electricity-generating technologies and their impacts in order to understand on which technologies the public is focussing support and to understand if this is correlated to the impacts of different electricity-generating technologies.

5.1.1.2 Public sample

A wide sample of the public was sought to take part in this survey in order for the results to be as representative of UK public opinion as possible. Sampling was carried out online as the survey was in electronic format in the Qualtrics survey software (www.qualtrics.com). Mailing groups and lists were identified as essential to sample in order to be able to gain as many responses in as short a time as possible. Sampling for the survey took place between January, 2011 and August, 2011. In addition to the supplementary bodies identified, representatives from the SPRIng Project steering committee and researchers from the SPRIng project were also asked if they would be willing to take part in the survey.

In total, 627 individuals took part in the public survey. As part of the survey, respondents were asked if they were willing to take part in a second public survey. The aims and objectives of the second public survey are presented in section 5.2.1.

Descriptions of technical issues were produced for the respondents to clarify and explain technical or scientific terms for both surveys. The descriptions (Appendix 7 Description of Sustainability Issues for Public Survey 1) gave descriptions of each of the issues that were asked to be considered as part of the survey. The idea behind this was to put all members of the public who were being consulted on an ‘equal footing’ before going ahead with the survey. The main aim of this was to minimise any bias in knowledge of the issues, so that the feedback on the indicator framework would come from individuals who shared the same level of information on the indicators as each other. In addition, another aim was for the public to be as informed about the indicators (how they were measured, where the data has come from and understanding their impacts) as possible. Therefore, by explaining the issues as they were being asked about them, the maximum understanding of the issues aimed to be achieved before an opinion was given.

5.1.1.3 Questionnaire development - Public Questionnaire 1

The first public questionnaire (Appendix 6 Public Engagement Survey 1) included Likert-style questions seeking to assess how favourable each individual believed each electricity-generating option to be. Similar Likert-style questions were also asked about the importance of the sustainability indicators (as part of the indicator framework) to be in assessing the sustainability electricity-generating options.

In addition to the above questions, the public were also asked for feedback on several more issues, evaluated below:

1) Awareness of proximity to electricity-generating power stations of installations from usual place of habitation.
2) Awareness of proximity from planned building of electricity-generating power stations of installations from usual place of habitation.
3) Opinion on the future UK electricity mix and relative contributions from the different electricity sources.
4) Suggestion of additional issues believed important to consider in evaluating electricity-generating options and why the given issue(s) (if any) is/are important.
5) Several question on personal and demographic information.

Question (1) was included in the questionnaire in order to determine whether opinions on particular indicators or electricity options might be related to an awareness of proximity of electricity-generating installations. Question (2) aimed to elucidate the same kind of information, but with regard to planned installations rather than currently operating ones.

5.1.1.3.1 Data collection

Samples were collected in the form of an online questionnaire using the Qualtrics survey software (www.qualtrics.com) As part of the sampling strategy, members of the public from many different backgrounds were targeted by using a variety of electronic newsletter advertisements. A total of 627 questionnaires were fully completed between January and August 2011. To maximise participation, each participant was offered the chance to take part in a prize draw for £50 worth of Amazon gift vouchers. The participants were also offered a chance to receive a summarised report on the finding of the public survey for taking part.

The feedback elicited from the members of the public through this consultation process can be considered as potentially low power. Although this is regarded as such in operations management (see Figure 4.1), it is also recognised that coordinated public action may also be very powerful and persuade governments to change courses of action, this is especially relevant to electricity generation, where many members of the public display particularly emotive opinions on the issues associated with electricity generation.

5.1.2 Questionnaire survey findings

5.1.2.1 Public perception of electricity-generating options

Public perception of the electricity-generating technologies is displayed in Figure 5.1. The most favourable technology was considered to be sun/solar power (with 91% favourable towards this source), followed by hydroelectric power (90% favourable), wind power (89% favourable), biomass-fired power (69% favourable), nuclear power (42% favourable), gas-fired power (18% favourable), coal-fired power (11% favourable) and oil-fired power (6% favourable).

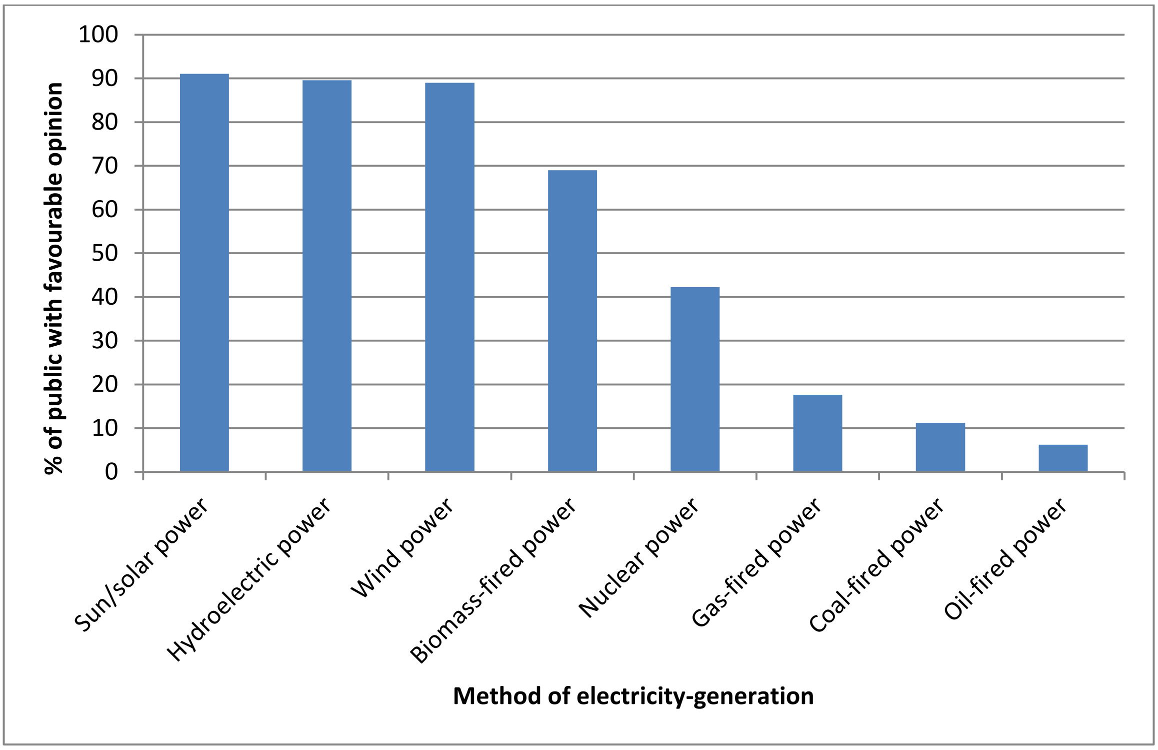


Figure 5.1. Public favourable opinion on electricity-generating technologies in the UK.

In terms of public opinion split on the favourability of nuclear power, the balance is relatively even with favourability at 42% and unfavourability at 40% in our population sample, which has also been reflected in earlier public surveys on nuclear power in the UK (Corner, et al., 2010; Ipsos Mori, 2011a).

Unfavourable opinions on electricity-generating options for the UK are represented in the graph below (Figure 5.2). Again, (as with the expert opinion on electricity options) the graph is an inverse of the favourable opinions graph displayed above, although the balance between favourable and unfavourable opinions is biased slightly towards favourable opinions on all of the electricity-generating options presented to the respondents.

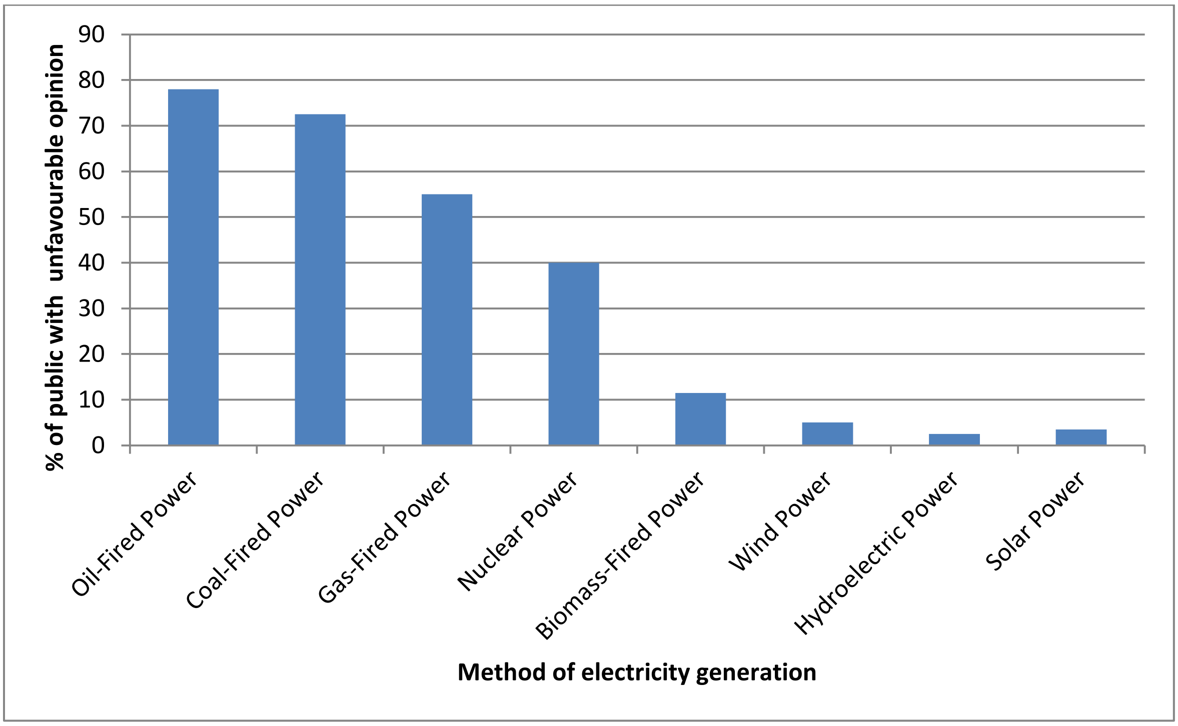


Figure 5.2. Public unfavourable opinion on electricity-generating technologies in the UK.

The most unfavourable technology was considered to be oil fired power (with 78% of the public surveyed believe this method as unfavourable), followed by coal-fired power (73% unfavourable), gas-fired power (55% unfavourable), nuclear power (40% unfavourable), biomass-fired power (12% unfavourable), wind power (5% unfavourable), solar power (4% unfavourable) and hydroelectric power (3% unfavourable).

5.1.2.1.1 The UK's future electricity mix

The public were also asked their views on the UK's future electricity mix. Participants were presented with the list of electricity-generating technologies currently used in the UK to generate electricity and the proportion that each technology contributed to the electricity mix was also specified. The public were then asked which technologies they would like to increase generation from, which they would like to decrease generation from, which technologies they would maintain at current generation levels and which they would stop generating from altogether. They were also given options of 'never heard of it', 'no opinion' and 'don't know'. The results are displayed in Figure 5.3. Solar power was the most popular power generation method which the public wanted to increase generation from, with 91% of people specifying that the penetration of solar power should be increased and only 2% specifying that power generation from solar technologies should be decreased or stopped. For the technologies that were rated as favourable (see Figure 5.1 – solar power, wind power, hydroelectric power and biomass-fired power), the percentage of favourability is broadly concordant with the percentage of people voting to increase the contribution from these sources. There was no one option where the percentage of responses was highest in the 'stop generating from this source' category. Oil-fired power was the least popular method to generate electricity, with 41% of people specifying that generation from this source should decrease, and 33% specifying that it should be stopped altogether.

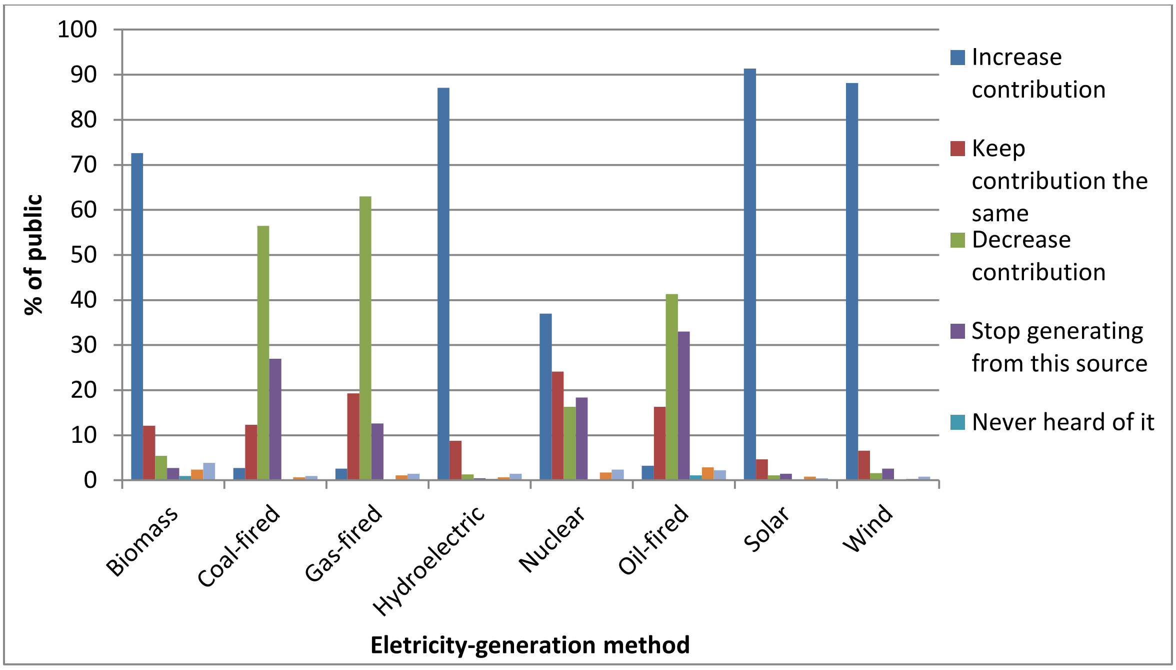


Figure 5.3. Graph showing the public opinion on the direction UK's future electricity mix. Participants specified whether they would increase, decrease, or stop generation of power from a number of electricity-generating methods currently used in the UK.

The results from this question allow further insight into the public opinion on electricity policy in the UK. The question on favourability towards electricity technologies does not allow the same inferences to be made about the direction of penetration (increased or decreased) of the less popular technologies as it did with the more favoured technologies. Taken at face value, it could be assumed that those technologies with a largely unfavourable opinion would also be chosen to stop generating. However, the results from this question on the unfavourable technologies display a more complex picture. For example, although oil-fired power, coal-fired power and gas-fired power were rated as 'unfavourable', the percentage of the public that wanted to stop generation from these sources were 3%, 27% and 13%, respectively. Instead, the majority of the public voted to decrease generation from these sources, with 63% voting to decrease generation from gas-fired power, 56% voting to decrease generation from coal-fired power and 41% voting to decrease generation from oil-fired power. Nuclear power remains the most split of the technologies as it did in the question on favourability, with 37% of respondents wanting to increase electricity generation from this method, 24% to maintain the current contribution, whilst 16% wanted to decrease its contribution and 18% voted to stop generating from this source completely.

5.1.2.1.2 Impact of the Fukushima disaster

An additional measure, outlined in the aims and objectives of this survey (see section 5.1) was identified after data collection began. The Fukushima nuclear power plant disaster occurred soon after the Tohoku earthquake and resultant tsunami on March 11th, 2011. This was some way through data collection for this public survey (collection began in January, 2011 and ended in August, 2011. A total of 478 responses were collected before the Fukushima disaster and 149 were collected after the disaster. Although the sample sizes are significantly different, a drastic change in public opinion following the events in Japan could be recorded in the post-disaster data and give clues to the extent of public concern over nuclear power.

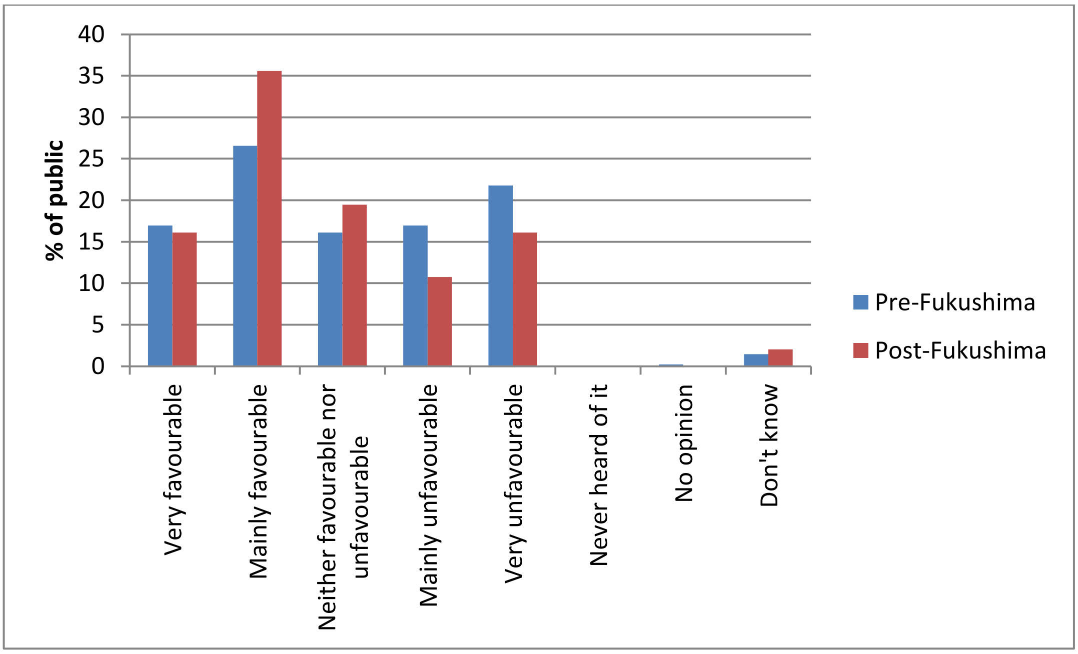


Figure 5.4. Public opinion of nuclear power prior to the Fukushima disaster, and after the Fukushima disaster (pre-Fukushima – *N*=478; post-Fukushima – *N*=149).

The results from the analysis on the favourability before and after the Fukushima disaster are displayed in Figure 5.4. From the samples taken over this period, the average favourability of nuclear power decreased slightly after the Fukushima disaster, with 17% rating nuclear power as very favourable before the accident, and 16% rating it as very favourable after the accident. This is only a very small decrease in ‘very favourable’ opinion and, conversely, the number of respondents rating nuclear power as ‘mainly favourable’ rose from 27% to 36%. Unfavourable opinion on nuclear power fell, ‘mainly unfavourable' beliefs dropped from 17% to 11% and 'very unfavourable' beliefs fell from 22% to 16%. The 'neither favourable nor unfavourable' rating rose from 16% to 19%.

An independent t-test was carried out on the sample to determine if there was a statistical significance between the mean responses of the two sample groups (samples taken before the Fukushima disaster, and samples taken after the Fukushima disaster). A mean of favourability of nuclear power was 3.00 in the pre-Fukushima sample and a mean of 3.23 in the post-Fukushima sample (1 = very favourable; 2 = mainly favourable; 3 = neither favourable nor unfavourable; 4 = mainly unfavourable; and 5 = very unfavourable). The t-test showed that there was no statistically significant difference between the two samples (p = <0.05) at the 95% confidence interval. Therefore, the results would suggest that the public opinion about nuclear power did not change after the Fukushima disaster. These results are supported by public surveys carried out by Ipsos MORI (2011b) and Friends of the Earth (FoE and GfK NOP, 2011).

Further sampling and analysis of the Fukushima-related issue is carried out in Section 5.2 further below.

5.1.2.2 Opinion on the impacts of electricity generation in the UK

Respondents to this survey were asked how important they believed 15 sustainability issues related to electricity-generation to be when assessing and comparing electricity-generating options. Overall, (based on average responses) respondents believed that 'water contamination from toxic substances' was the most important issue to consider, followed by 'land contamination from toxic substances', then 'greenhouse gas emissions'. The full list of the ranking of the sustainability issues is listed in Table 5.1.

Table 5.1. Public ranking of sustainability issues in the UK.

Sustainability Issue	Rank Number	
Water contamination from toxic substances	1	Most important
Land contamination from toxic substances	2	
Greenhouse gas emissions	3	
Remaining world fuel reserves	4	
Human health impacts from toxic substances (excluding radiation)	5	
Ozone layer depletion	6	
Waste management required by future generations	7	
Human health impacts from radiation	8	
Civilian fatalities due to large accidents	9	
Reliability of electricity generation and ability to respond to peak demand	10	
Worker fatalities from work-related accidents	11	
UK energy security: diversity of fuel supply and ability to store fuel for future use	12	
Acid rain	13	
UK energy security: avoiding imports of fuels	14	
Cost of electricity	15	Least important

The least important sustainability issue is considered to be the cost of electricity, followed by the avoidance of fuel imports, then acid rain. The split in importance versus unimportance votes for each of the indicators can be seen in Figure 5.5 and Figure 5.6. Figure 5.5 displays the importance of environmental, technical and economic sustainability indicators and Figure 5.6 displays importance of the social sustainability indicators.

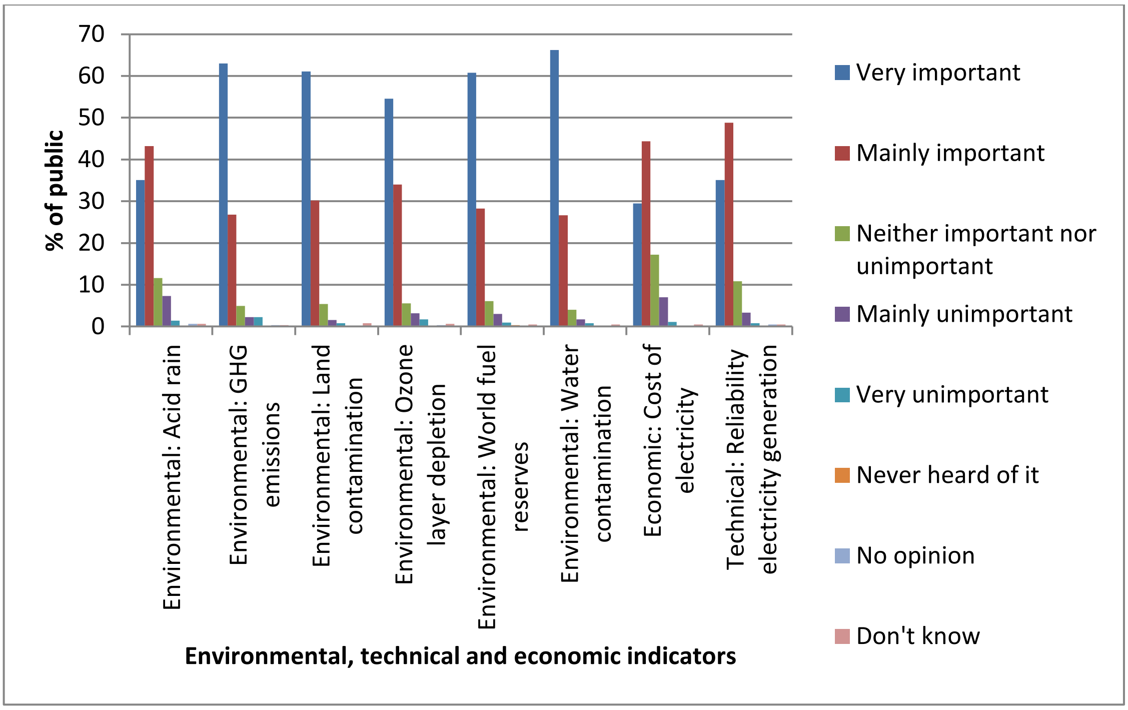


Figure 5.5. Public opinion on the importance of the environmental, technical and economic indicators included in the first pubic survey.

Out of the environmental indicators water contamination receieved the most votes for ‘very important’ issue (and was ranked most important over all sustainability indicators) with 66% of respondents specifying this, followed by greenhouse gas emissions (63%) and land contamination and remaining world fuel reserves were voted as very important issues by 61% of the respondents. Combining the ‘very important’ and ‘mainly important’ votes ranks the issues as shown in Table 5.1. Reliability of electricity generation, cost of electricity and acid rain all receievd the most votes for being ‘mainly important’ (at 49%, 44% and 43%, respectively).

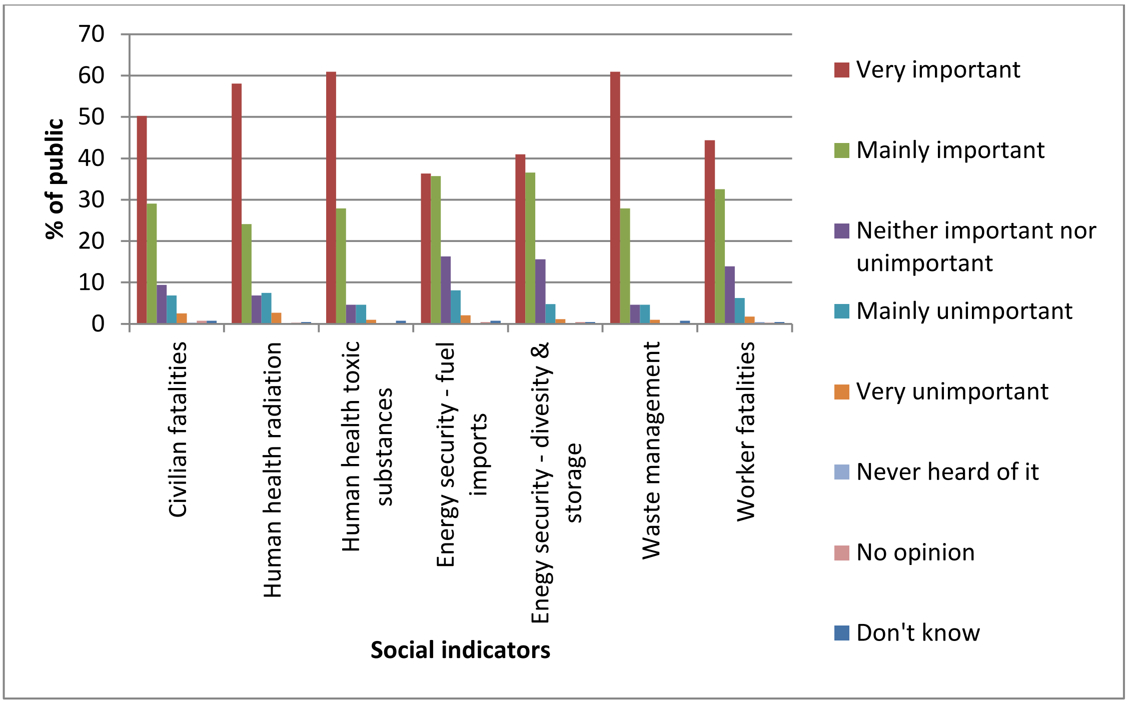


Figure 5.6. Public opinion on the importance of the social indicators included in the first pubic survey.

Feedback on the importance of the social indicators was also mixed; waste management, human health effects from toxic substances and human health effects from radiation were all voted overall as very import (receiving 61%, 61% and 58%, respectively). Civilian fatalities and worker fatalities also received majority ‘very important’ ratings at 50% and 44%, respectively. Feedback on energy security – fuel imports and diversity & storage were more mixed, fuel imports was voted as very important by 36% of respondents and mainly important also by 36% respondents and diversity & storage 41% for being very important and 37% of the respondent vote for being mainly important.

Of all of the sustainability indicators, the issue that received the most votes on unimportance were civilian fatalities and human health effects from radiation (both voted 3% very unimportant and 7% mainly unimportant) followed by fuel imports (2% very unimportant and 8% mainly unimportant). However, from the findings of the public opinion of the importance of sustainability impacts of electricity generation, the results show that all of the issues, overall are considered important and the tendency is for the public to vote for them as such.

5.1.2.2.1 Correlation of sustainability values

A bivariate correlation analysis was carried out on the ratings of the sustainability indicators by each public survey respondent. All of the indicator importance ratings were found to be correlated to the importance of the other indicators. This is not surprising as the indicators are already defined as important issues to the sustainability of UK electricity generation through the research that has been done in defining them, and the public were more likely than not to rate an indicator as 'important' (as all, or many of the issues identified are relevant to the public and have varying impacts on their lives). However, it should be noted that all of the correlations between each set of two indicators were positive (high ratings of indicators are correlated) and the most significant correlations were between: human health impacts from radiation and human health impacts from toxic substances (r = 0.79 and p = <0.001); worker fatalities and human health impacts from toxic substances (r = 0.71 and p = .000); land contamination from toxic substances and water contamination from toxic substances (r = .74 and p = .000); and human health impacts from toxic substances and water contamination from toxic substances (r = .73 and p = .000), where r is the Pearson correlation coefficient and p is the statistical significance of the correlation (a value of less than 0.05 is considered significant).

5.1.2.2.2 Correlation of nuclear power favourability and sustainability values

A multiple regression analysis was carried out using nuclear power favourability as the dependent variable and the 15 rated sustainability indicators as the predictor variables in order to identify if nuclear power favourability or unfavourability was positively or negatively correlated to importance rating of the sustainability indicators. For this multiple regression model, an examination of the prediction of nuclear power favourability from rating of the importance of one or more of the sustainability indicators was sought. The model results showed that there were no significant predictor sustainability issues to indicate support for nuclear power, i.e. there was no direct relationship between the rating of nuclear power and the rating of any of the sustainability indicators

5.1.3 Summary of the first stage public consultation

The first stage public consultation has identified the respondents' favourability rating towards different methods of electricity generation, the technologies that they would like to increase penetration of and decrease penetration of in the UK and the most important and least important sustainability indicators in the context of public opinion. In addition, analysis of the responses prior to, and after the Fukushima nuclear power disaster of Japan appear to indicate robust support for nuclear power amongst those that already considered it favourable. No significant negative or positive correlation was identified between support for nuclear and rating of the sustainability indicators.

Solar, hydroelectric and wind power were considered to be the most favourable options from which to generate electricity (with 91%, 90% and 89% approval ratings, respectively) and oil-, coal- and gas-fired power were considered to be the least favourable sources of electricity (with 78%, 73% and 55% disapproval rating, respectively).

The most important sustainability indicators (based on average rating) were considered to be (in order of importance), water contamination from toxic substances, land contamination from toxic substances and greenhouse gas emissions. The indicators with the lowest rating were considered to be cost of electricity, fuel imports avoided and acid rain. The high rating of water and land contamination could be related to individuals placing high importance on their local environment. Although climate change and the effect of greenhouse gas emissions are widely recognised and many members of the public display some understanding of the issues, many individuals in the UK may not associate this impact with a direct detriment. Water and land contamination are associated with toxicity, leading to problems with water supply and land use and disease. Currently, the exact health and environmental detriment of climate change to the UK public is unclear. Although the bottom three rated indicators are also important issues to the UK public, in the context of the more controversial and potentially higher impact issues, these issues may not be considered as urgent or detrimental. For example, emissions which cause acid rain are now controlled by legislation (the main contributors to acid rain impact in the 1980s was from fossil fuel power stations, which now have desulphurisation units to minimise this impact. In addition, the UK public may not associate energy security and the deterioration of international relations to be correlated to fuel imports. Finally, the cost of electricity was rated as the least important issue. This is surprising when consideration of the rising costs of energy generally and electricity specifically and the prevalence of these issues in the news is taken into account. However, this could be explained by the fact that this issue is being assessed against many other controversial issues.

5.2 Multi-Criteria Public Perspectives on Electricity Generation in the UK

5.2.1 Aims and objectives of the multi-criteria public questionnaire

The overall aim of the public multi-criteria survey is to identify what the public believe are the main issues associated with the sustainability assessment of electricity-generating technologies in the UK (focussing on the three tiers of sustainability – techno-economic, environmental and social impacts) through the use of preference weighting used for decision-analytic problems. The derived weights take into account all significant electricity-generating options in the UK and are not solely nuclear focussed. This allows nuclear power to be modelled against all other electricity options in order to determine the 'most sustainable' option, or options based on the public weighting. Additionally, public preferences on the importance of the sustainability impacts of electricity-generating technologies are sought, so that the multi-criteria decision model takes a slightly more objective angle (as the public often do not understand which technologies have certain impacts). The specific objectives of the public consultation include:

- to determine if public opinion on sustainability issues had changed over the time since the first public survey;

- to determine the reasons for change in public opinion on nuclear power;

- to determine external factors that might have influenced a change in public opinion on the above issues;

- to determine awareness of the UK government's intention to build a new fleet of nuclear power stations;

- to determine the level of support for nuclear power amongst the public;

- to identify any correlation between environmental objectives and support for certain electricity-generating options; and

- to generate MCDA weights for the general public stakeholder group in order to feed into the electricity scenario assessment in chapter 8 of this thesis.

The participants who agreed to take part in the second public survey were emailed the link to the second survey (in January, 2012). A total of 231 individuals took part in the second public survey.

Further detail on the research methodology used in the public survey exercise can be found in section 5.2.2. Section 5.2.3 details the findings from the public survey exercise, section 5.2.4 compares to expert stakeholder results to the public findings and section 5.2.5 discusses these results and concludes the finding from the public survey.

5.2.2 Stage 2 research methodology

This stage of the public consultation has sought to determine public preference weights for the indicator framework developed by Stamford (2012), in addition to the sustainability pillars (techno-economic, environmental and social) and the electricity technologies. The set of indicators presented to the public was larger than the set presented in the first public question – 25 indicators were presented in the MCDA questionnaire, which were condensed from the 43 indicators in the final indicator framework (see section 3.5). Again, the indicators were simplified in order to aid understanding of the sustainability issues surrounding electricity generation. These indicators can be found in Appendix 8 Public Engagement Survey 2.

5.2.2.1 Public sample

In order to be as representative of UK public opinion as possible a wide sample of the public was sought to take part in this survey. As part of the survey, respondents were asked if they were willing to take part in a second public survey. A total of 231 respondents took part in the second public survey. Sampling for the survey took place between January, 2012 and February, 2012.

Non-technical summaries of the technical issues were produced for the respondents to clarify and explain technical or scientific terms for both surveys. The summaries (Appendix 9 Description of Sustainability Issues for Public Survey 2) gave descriptions of each of the issues that were asked as part of the survey. Again, the idea behind this was to put all members of the public who were being consulted on an ‘equal footing’ before going ahead with the survey. As the number of indicators had increased from the first public survey and some had been changed, it was important that the respondents understood what they were being asked. The main aim of this was to minimise any bias in knowledge of the issues, so that the feedback on the indicator framework would come from individuals who shared the same level of information on the indicators as each other. In addition, another aim was for the public to be as informed about the indicators (how they were measured, where the data has come from and understanding their impacts) as possible. Therefore, by explaining the issues as they were being asked about them, the maximum understanding of the issues aimed to be achieved before an opinion was given.

5.2.2.2 Questionnaire development - public questionnaire 2

The second public questionnaire (Appendix 8 Public Engagement Survey 2) included one Likert-style question seeking to assess how favourable each individual believed each electricity-generating option to be. The majority of the remainder of the questions within the survey were aimed at eliciting weights for: electricity-generating options (by using a simple rank-style question); each of the indicators (by using a simple multi-attribute value technique); and finally, weights for each of the sustainability aspects – techno-economic, environmental and social (derived using the AHP technique – see section 2.4.3 for a description of this method).

In addition to the above questions, the public were also asked for feedback on several more issues, evaluated below:

1) Nuclear issues, including: opinion on nuclear power and whether it has changed within the last year; awareness of government plans to build a new generation of nuclear power stations; support for the new nuclear plans.

2) Environmental issues, including: concern about climate change and global warming and environmental issues; and practical action on climate change and environmental degradation, including campaigning.
3) Opinion on the viability of various low-carbon electricity options in reducing the UK’s greenhouse gas emissions.

The first set of questions have been included in order to gain further information on the support for nuclear power, whether support is likely to be affected by further building of nuclear power stations. The motivation for including the second set of questions in the questionnaire was to elucidate whether support for nuclear power is correlated to support for environmental and climate change causes. Finally, the last set of questions are asked in order to determine which electricity options the public believe are a viable option, or options for combating climate change.

5.2.2.2.1 Data collection

Samples was performed using an online questionnaire using the Qualtrics survey software (www.qualtrics.com). Between January and February, 2012 a total of 231 questionnaires were fully completed. To maximise participation, each participant was offered the chance to take part in a prize draw for £50 worth of Amazon gift vouchers. The participants were also offered a chance to receive a summarised report on the finding of the public survey for taking part.

5.2.3 Questionnaire survey findings

5.2.3.1 Public perception of electricity-generating options

The public were first asked to consider which electricity options they considered favourable and unfavourable. The results of favourable and unfavourable opinion from the second public survey and first public survey are displayed in Figure 5.7 and Figure 5.8. The ranking in favourability in the second public survey is the same as the ranking in the first public survey. From the second public survey response, solar power is voted as the most favourable option to generate electricity, with 92% of the public specifying that this technology is favourable (up from 91% in the first public survey). Hydroelectric power follows with 89% public approval (down 1% from 90%) and favourability on wind power has also decreased from 89% in the first survey, to 86% in the second survey. Favourability for biomass-fired power also drops from 69% in the first public survey, to 68% in the second public survey. The favourability of nuclear power rose from the first public survey from 42% to 43%, as did the favourability of gas-fired power (18% to 23%). Coal-fired power favourability dropped from 11% to 9%, and the favourability of oil-fired power also fell (6% to 4%).

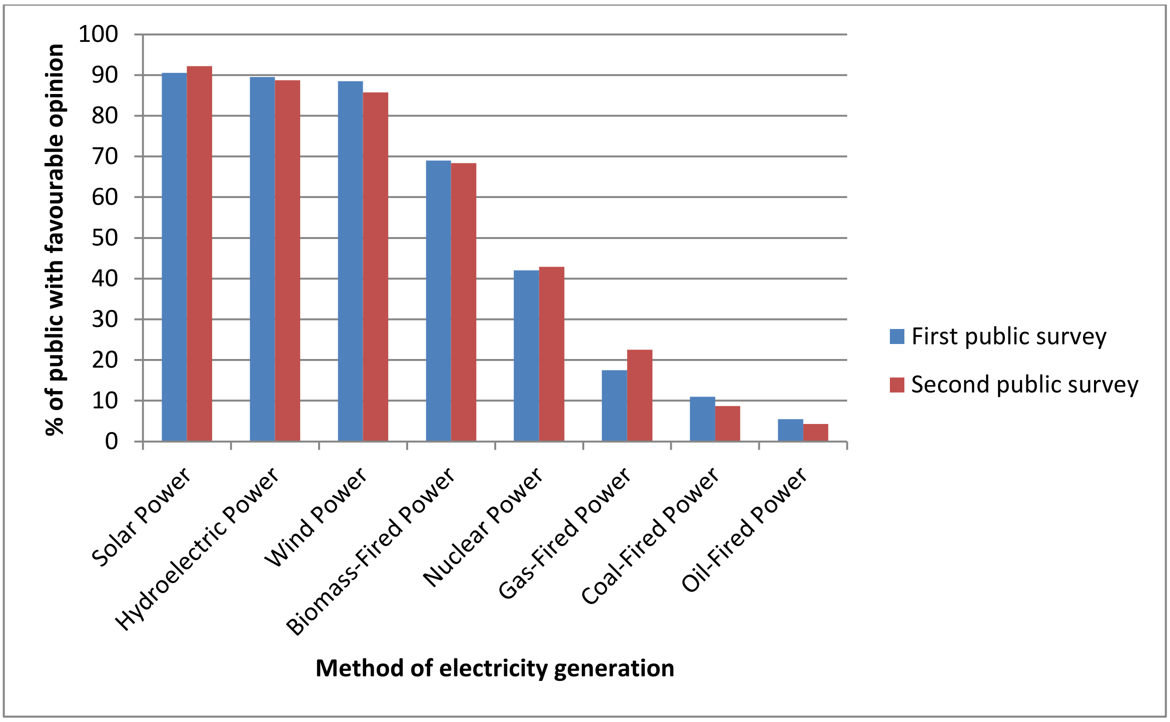


Figure 5.7. Graph showing the difference in favourable opinion on electricity-generating technologies between the first and second public surveys. (First public survey, *N* = 627; second public survey, *N* = 231).

The ranking of unfavourability in the second public survey is mostly the same as the ranking in the first public survey, apart from the ranking of hydroelectric power and solar power, whose rankings were reversed from the first public survey. From the second public survey response, oil-fired power is voted as the most unfavourable option to generate electricity, with 77% of the public specifying that this technology as unfavourable (down from 78% in the first public survey). Coal-fired power follows with 75% public disapproval (up 2% from 73%) and unfavourability of gas-fired power decreased from 55% in the first survey, to 52% in the second survey. Disapproval of nuclear power also drops from 40% in the first public survey, to 39% in the second public survey. The disapproval of biomass-fired power rose from the first public survey from 12% to 15%, as did the disapproval of wind power (5% to 9%). Solar power disapproval dropped from 4% to 2%, and hydroelectric power disapproval remained the same across both surveys (3%).

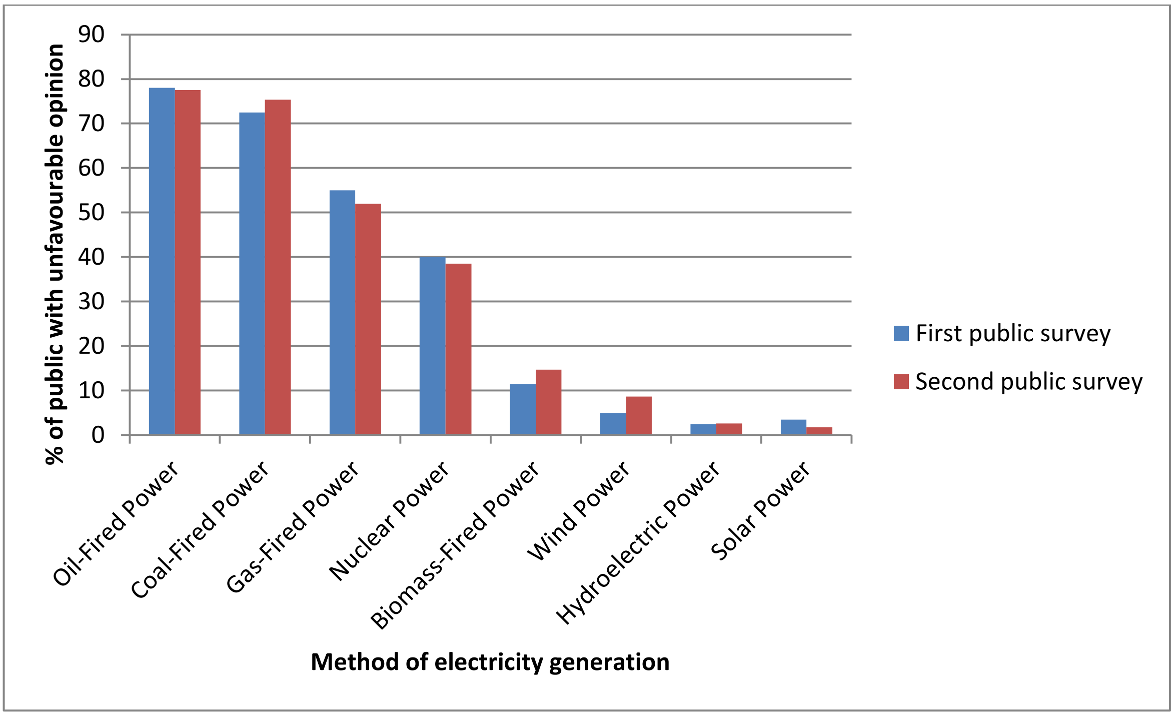


Figure 5.8. Graph showing the difference in unfavourable opinion on electricity-generating technologies between the first and second public surveys. (First public survey, *N* = 627, second public survey, *N* = 231).

5.2.3.2 Public perspectives on nuclear issues

Following on from the analysis on public perception change on nuclear power since the Fukushima disaster of 2011, the public were asked if their opinion on nuclear power had changed in the last year. A majority of the respondents specified that their opinion on nuclear power had not changed within the last year (84%) and 16% said that their opinion on nuclear power had changed in the past year (see Figure 5.9).

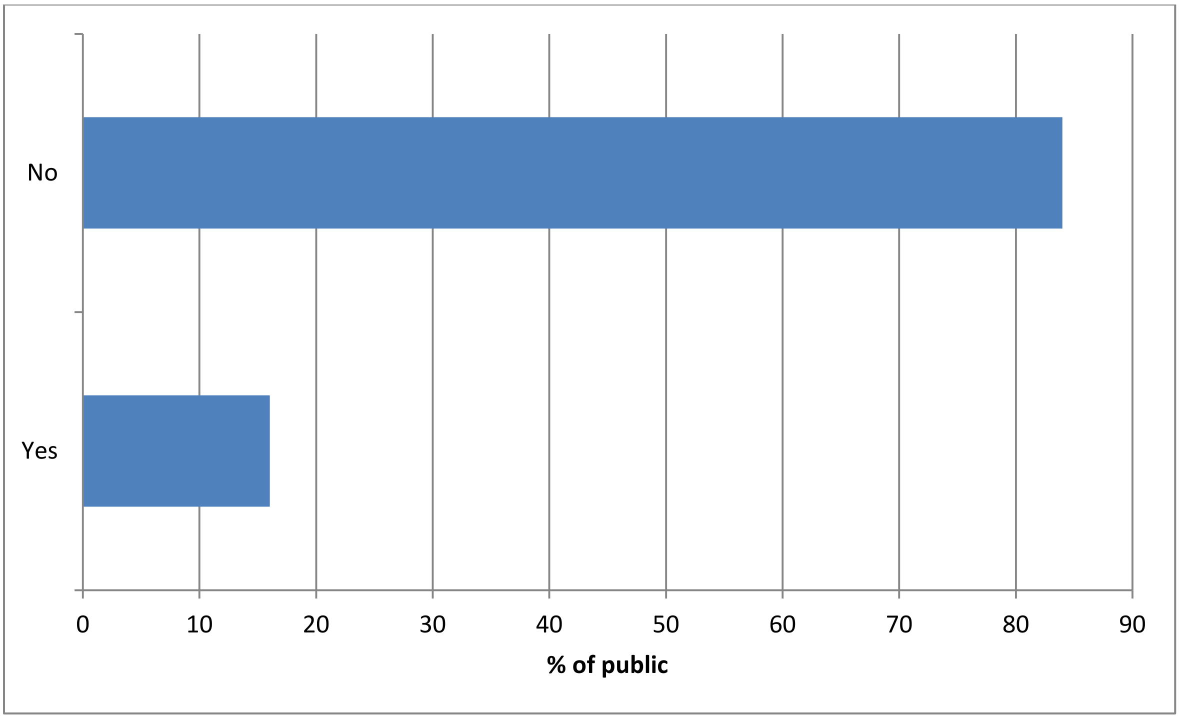


Figure 5.9. Graph showing response to the question 'Has your opinion on nuclear power changed within the past year'.

The respondents who answered 'yes' to the previous question were then asked if their opinion on nuclear power had become more positive, or more negative. More than a half (59%) of the respondents specified that their opinion had become more positive and 41% specified that their opinion had become more negative (see Figure 5.10). Respondents were asked a further open-ended question regarding the reason for their change in opinion. Of those that indicate a more negative opinion, the Fukushima disaster was overwhelmingly specified as the reason for the change in opinion.

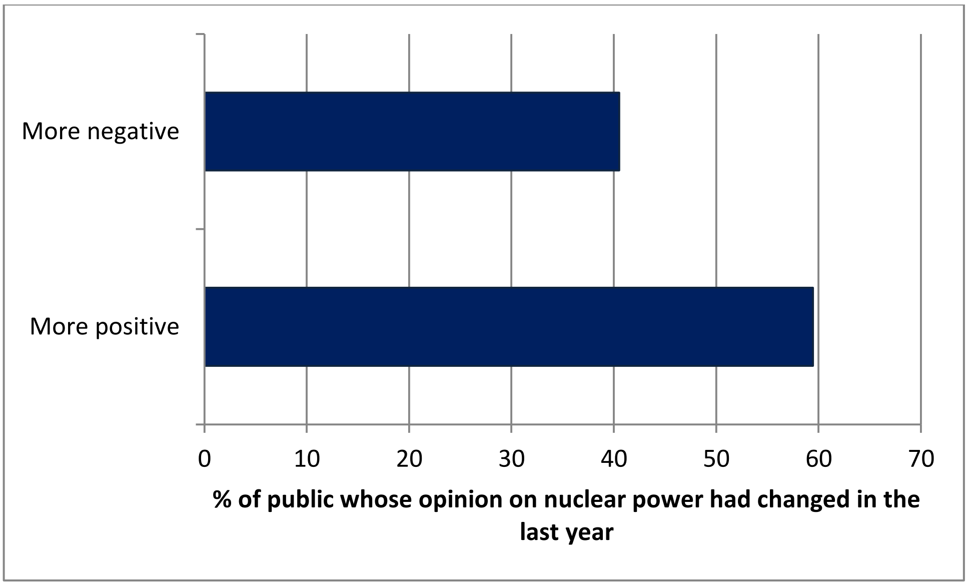


Figure 5.10. Graph showing change in opinion of respondents whose opinion on nuclear power had changed within the past year.

For the respondents who indicated a more positive opinion, a variety of reasons were specified for this change, although, in addition to having a negative effect on some respondents' opinion of nuclear power, several respondents indicated that the Fukushima disaster had made their opinion of nuclear power more positive, and this opinion was largely put down to a belief that such a disaster would not happen in the UK or would be extremely unlikely to happen and in addition, a belief that the public response of some at home and abroad on the disaster had been an overreaction.

The participants in the second public survey were then asked a series of questions regarding nuclear power expansion and energy policy in the UK context. The questions and the results are presented in Figure 5.11. The results indicate that there is a split in acceptance of the current Government plans for the next generation nuclear power programme in the UK, with 44% of people of the strongly agree of tend to agree opinion and 44% of the strongly disagree or tend to disagree opinion.

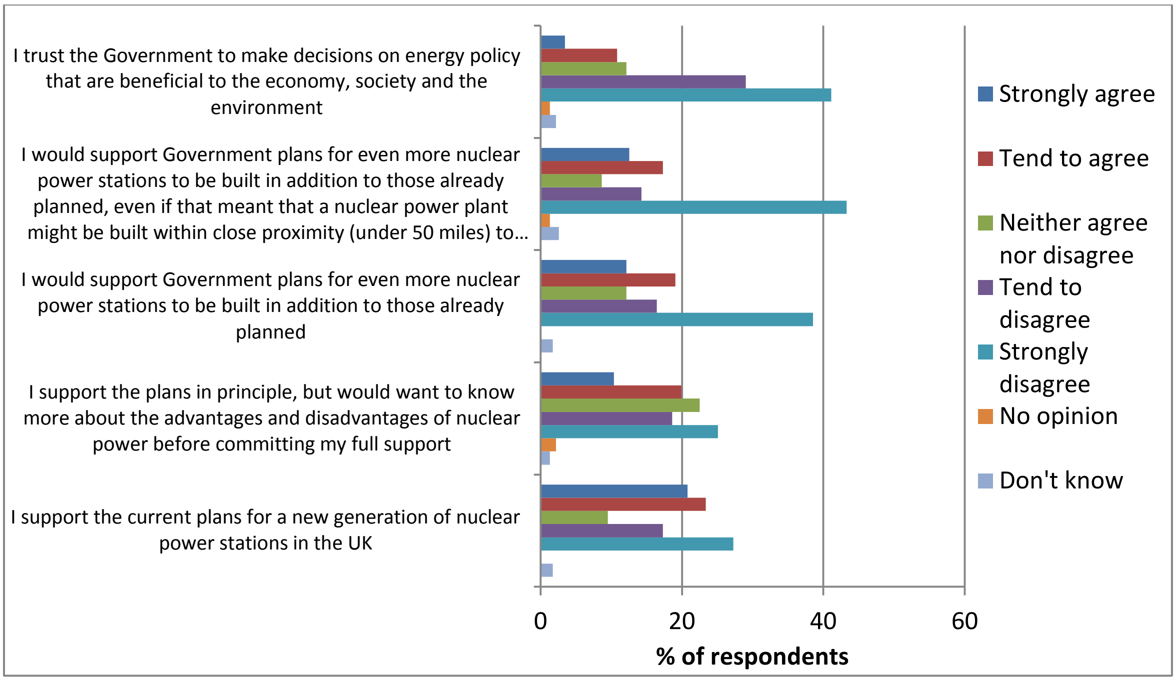


Figure 5.11. Graph showing agreement/disagreement on several issues regarding nuclear policy and energy policy problems in the UK.

In addition, the majority of participants in the survey specified that they would not support further expansion of the nuclear power programme if it meant their homes would be sited within 50 miles of a new power station. The opposition to nuclear power expansion appears only partially founded on location and proximity to home, as many respondents specified that they would not support Government plans to build any more nuclear power stations than those that are currently planned.

Overwhelmingly, there is little public trust in the Government to make sustainable energy policy decisions for the future.

5.2.3.3 Public perspectives on the ability of low-carbon technologies to reduce the national carbon footprint

The participants in this survey were asked about several low-carbon electricity options and their belief in whether any of the options could contribute to lowering the UK's carbon emissions in the electricity sector. Most agreement for this question was centred on wind and solar power, with 85% and 89% respectively agreeing that these technologies could play a significant part of the UK's future low carbon electricity mix. Nuclear power was the least endorsed electricity technology under this measure, with only 56% of the respondents agreeing that it could significantly lower UK carbon emissions.

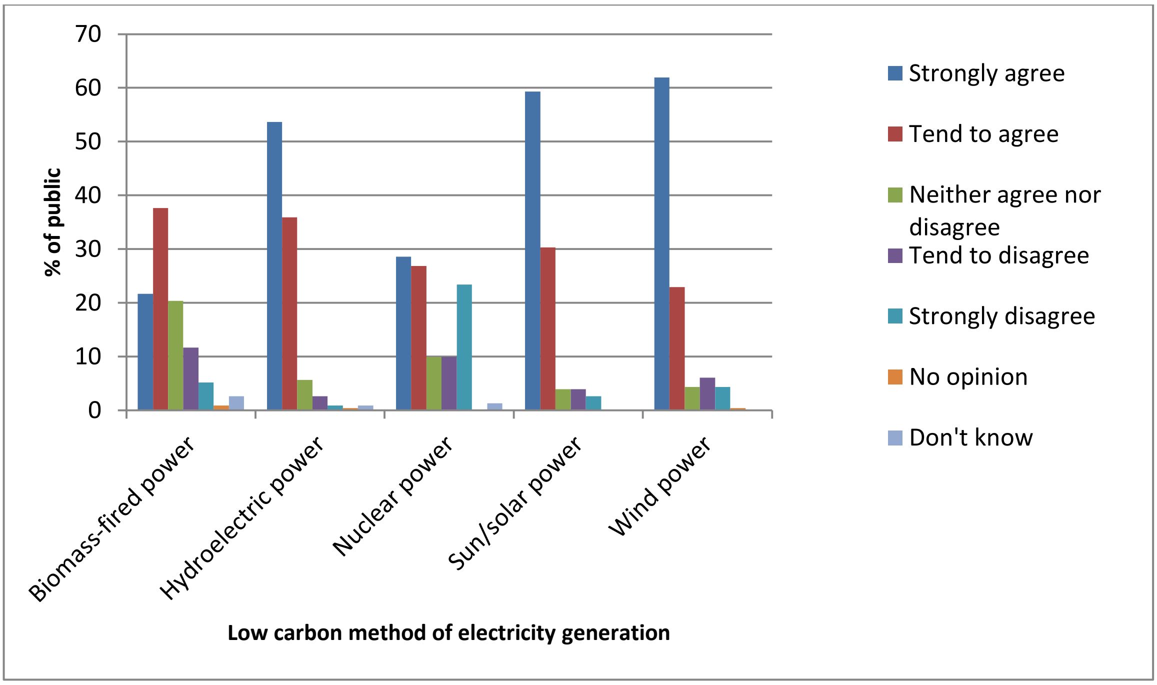


Figure 5.12. Graph showing agreement/disagreement on the ability of several low carbon methods of electricity generation to reduce the UK's carbon footprint.

5.2.3.4 Multi-criteria perspectives on electricity-generating technologies

The public were asked to carry out a simple ranking of the electricity options presented to them (in alphabetical order: biomass-fired power, coal-fired power, gas-fired power, hydroelectric power, nuclear power, oil-fired power, solar power and wind power). In addition, they were given the option to specify an electricity technology not considered in the analysis which they believed to be important. The electricity options were rated in order of preference, starting with '1' as the best/most favourable option, and '8' or '9' as the worst or least favourable option.

The range of public rankings for each electricity-generating option are displayed in Figure 5.13. The boxplot of the distribution of stakeholder rankings displays the lower quartile, the upper quartile and the 25th, 50th and 75th percentiles.

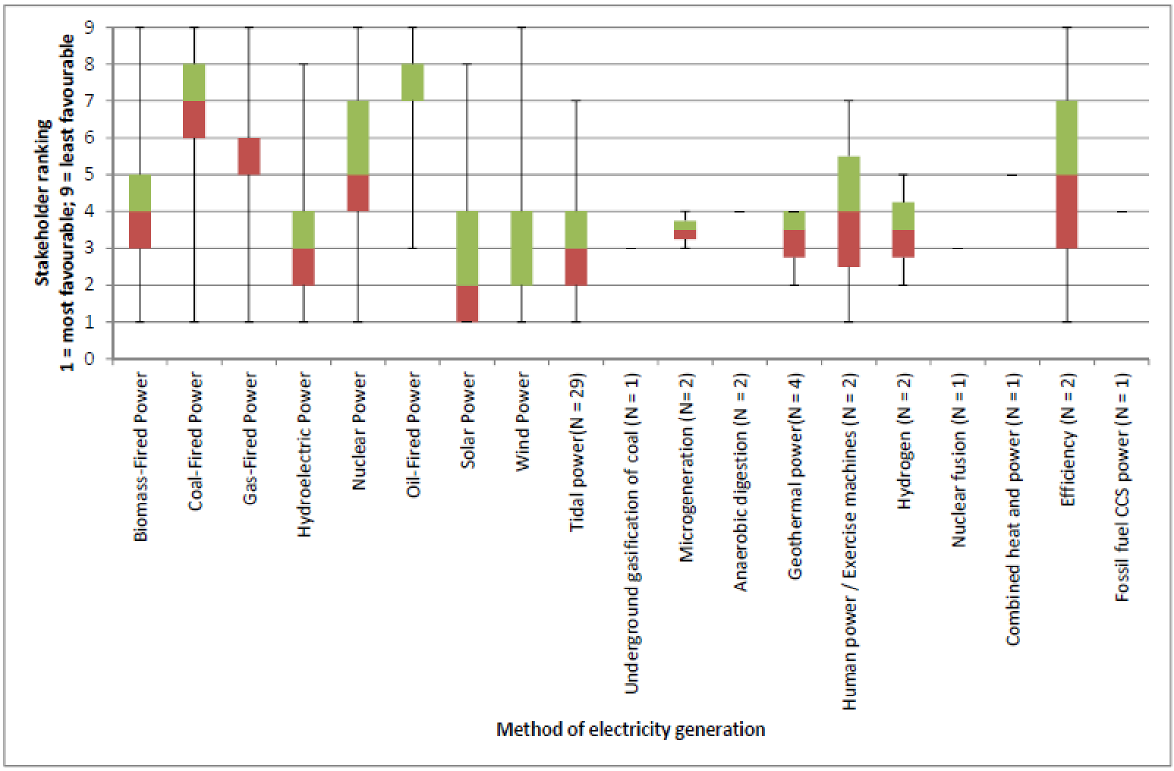


Figure 5.13. Boxplot displaying the distribution of stakeholder rankings for UK electricity options. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

Amongst the eight electricity generation methods rated by the public, most consensus was reached on the rating of oil-fired power as unfavourable. Coal- and then gas-fired power were rated as the next least preferred options, although the rating for coal-fired power displays a wider rating and therefore split in opinion of this technology compared to oil-fired and gas-fired power. Nuclear power is the next most favourable option, with a median ranking of 5. Biomass-fired power receives a median ranking of 4 and exhibits a smaller distribution of data around the median than nuclear power. Hydroelectric power is the third most favourable option, and is followed by wind, and solar power as the most favourable electricity option. Several additional technologies were suggested by the public and included: tidal power (suggested by 29 respondents); underground gasification of coal (one respondent); microgeneration (two respondents); anaerobic digestion (two respondents); geothermal power (four respondents); human power (two respondents); hydrogen (two respondents); nuclear fusion (one respondent); combined heat and power (one respondent); efficiency (two respondents); and fossil fuel CCS power (one respondent). Out of the 11 options suggested, tidal power was ranked the best, followed by underground gasification of coal and nuclear fusion. As the sample sizes for these technologies are small, their rankings are relatively unreliable, but do give an indication of alternative power generation methods being considered by the public currently.

5.2.3.5 Multi-criteria perspectives on the SPRIng sustainability indicators

Each member of the public was then asked to carry out a simple multi-attribute value theory ranking of the options presented to them in order of sustainability aspect, starting with techno-economic indicators, then environmental and finally social indicators. Each respondent rated the 25 indicators in order of importance within each of the indicator groups. The public specified the relative importance of each indicator, by assuming a hypothetical scale of 0-100 and first beginning by assigning the most important indicator a score of 100. They were then asked to then assign each subsequent indicator to a position on the scale (0-100) that they thought represented its relative importance in relation to all the other indicators. They were also asked to assign indicators that were considered equally important the same value and to assign the least important indicator a score of 0.

5.2.3.5.1 Total sample results

A boxplot of the total sample results for all of the public rated sustainability indicators can be seen in Figure 5.14. The indicators are arranged in terms of importance within their impact groups, starting with techno-economic indicators, then environmental, and finally, social. The environmental indicators display the highest average median (50th percentile) rating at 58.6, followed by techno-economic indicators at 52.3 and finally, social indicators at 51.8. Across all of the indicators, most consensus was reached on the importance of global warming potential, with the majority of public agreeing that global warming potential is one of the most important issues to consider in a sustainability assessment of electricity-generating technologies. In addition, relatively high agreement was reached on depletion of world fuel reserves, land contamination from toxic substances and cost of electricity. Overall, the environmental indicators display the most consensus and the least distribution, followed by the techno-economic indicators, and then the social indicators, which proved to be the most controversial measures, on average, amongst the public. The most controversial issues were spread of nuclear weapons technology, civilian fatalities due to large accidents, and financial support from government for various electricity-generating options.

Figure 5.14. Boxplot displaying the distribution of public rankings for the sustainability indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

5.2.3.5.2 Techno-economic sustainability indicators

The techno-economic group of indicators consisted of six measures altogether. A boxplot of the results for the ratings of the techno-economic indicators can be seen in Figure 5.15. The indicators are displayed in the order of presentation in the survey.

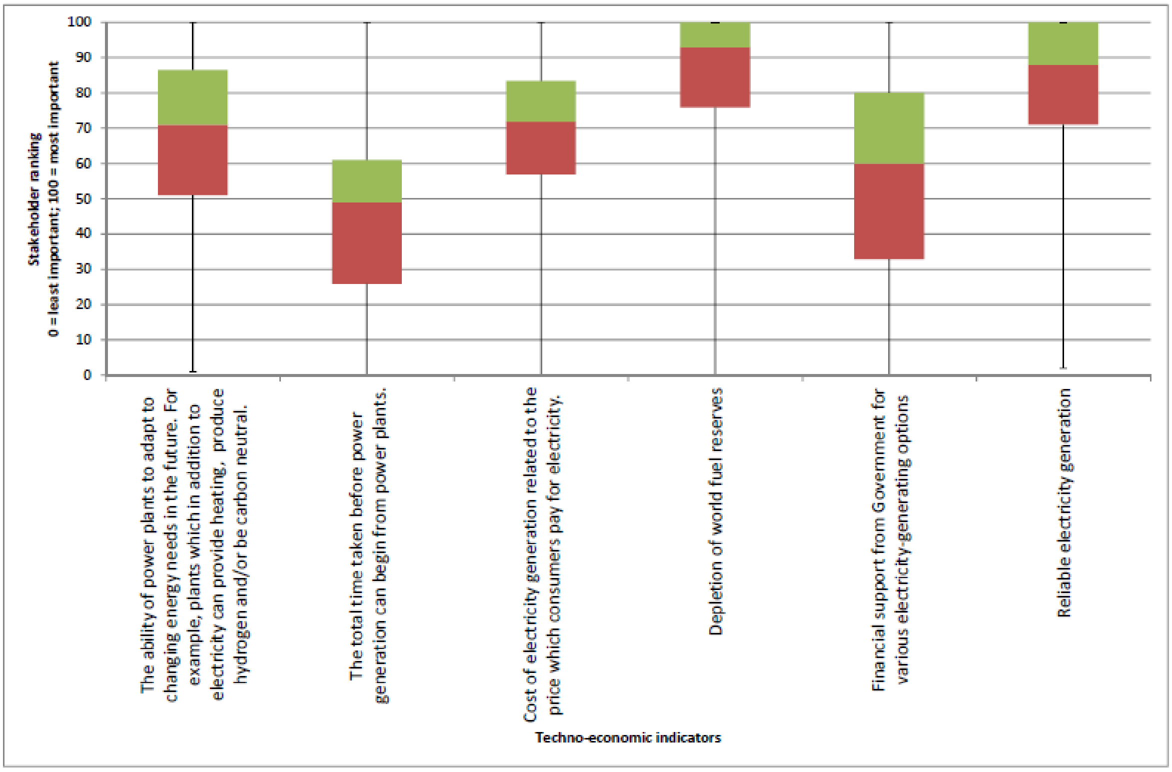


Figure 5.15. Boxplot displaying the distribution of public rankings for the techno-economic sustainability indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

Across the techno-economic indicators, most consensus was reached on the importance of depletion of world fuel reserves, followed by the cost of electricity. The most important techno-economic indicator is considered to be depletion of world fuel reserves, followed by reliability of electricity generation. The least important techno-economic indicator was considered to be financial support from Government for various electricity-generating technologies. The most controversial issues amongst the techno-economic indicators were: financial support from Government for various electricity-generating technologies and ability of power plants to adapt to changing energy needs in the future.

5.2.3.5.3 Environmental indicators

Secondly, the environmental indicators were rated. This group consisted of nine indicators. A boxplot of the results for the ratings of the environmental indicators can be seen in Figure 5.16. The indicators are displayed in the order of presentation in the survey.

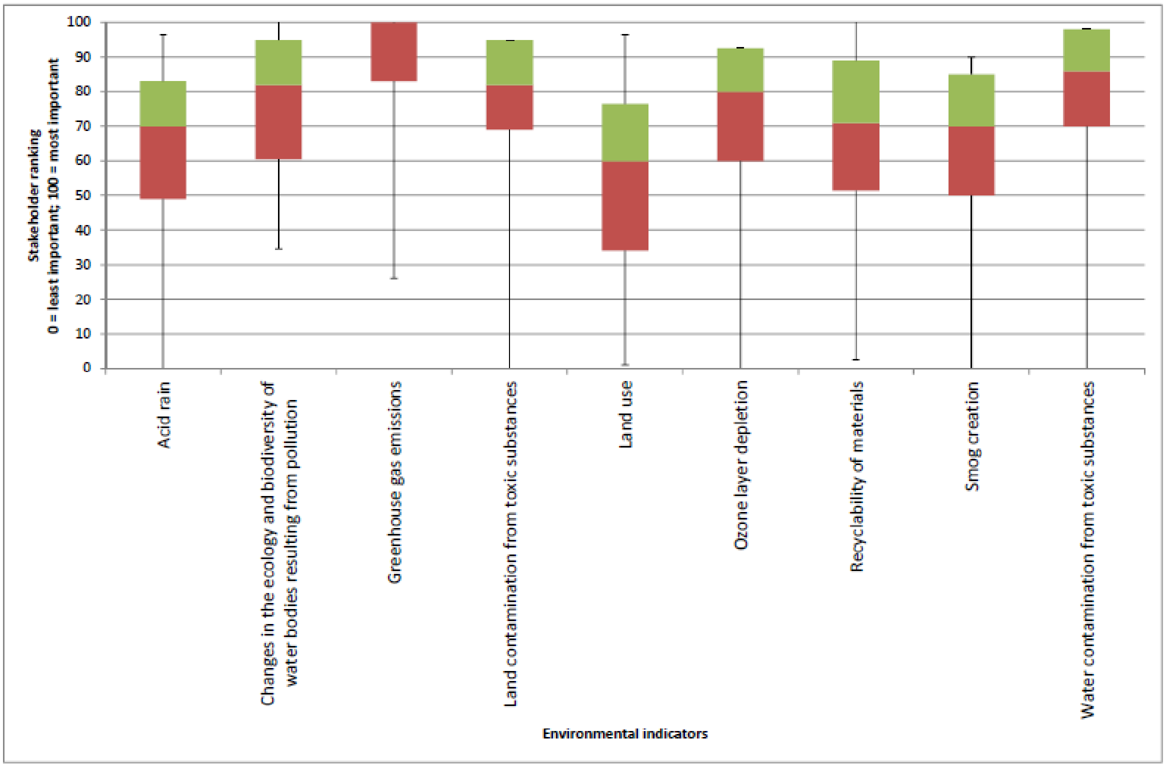


Figure 5.16. Boxplot displaying the distribution of public rankings for the environmental sustainability indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

Across all of the indicators, most consensus was reached on the importance of global warming potential, followed by land contamination from toxic substances. The most important environmental indicator is considered to be global warming potential, followed by water contamination from toxic substances and land contamination from toxic substances. In the first public survey, the top three environmental indicators rated by the public were (in order of importance): water contamination from toxic substances; land contamination from toxic substances; and greenhouse gas emissions, which is the same top three issues identified here, although greenhouse gas emissions are now considered to be the most important issue. The least important environmental indicators were considered to be land use, acid rain and smog creation. In the first stage of public consultation, smog creation and land use were not included in the analysis as the survey only considered a concise set of 15 indicators (including techno-economic, environmental and social aspects). However, acid rain was rated as one of the least important indicators in the first stage. The most controversial issues amongst the environmental indicators were: land use; recyclability of materials; and smog creation which all displayed the widest distribution in ratings.

5.2.3.5.4 Social indicators

The social indicators were then rated by the public participants and this set consisted of ten measures altogether. A boxplot of the results for the ratings of the social indicators can be seen in Figure 5.17. The indicators are displayed in the order of presentation in the survey. Across all of the social indicators, most consensus was reached on the importance of human health impacts from toxic substances, employment and waste management required by future generations. The most important social indicator is considered to be human health impacts from toxic substances, followed by waste management required by future generations. The least important techno-economic indicators were considered to be spread of nuclear weapons and technology and local community investment. The most controversial issues amongst the social indicators were: spread of nuclear weapons and technology; civilian fatalities due to large accidents; and worker fatalities from work related accidents, which all displayed the widest distribution in ratings.

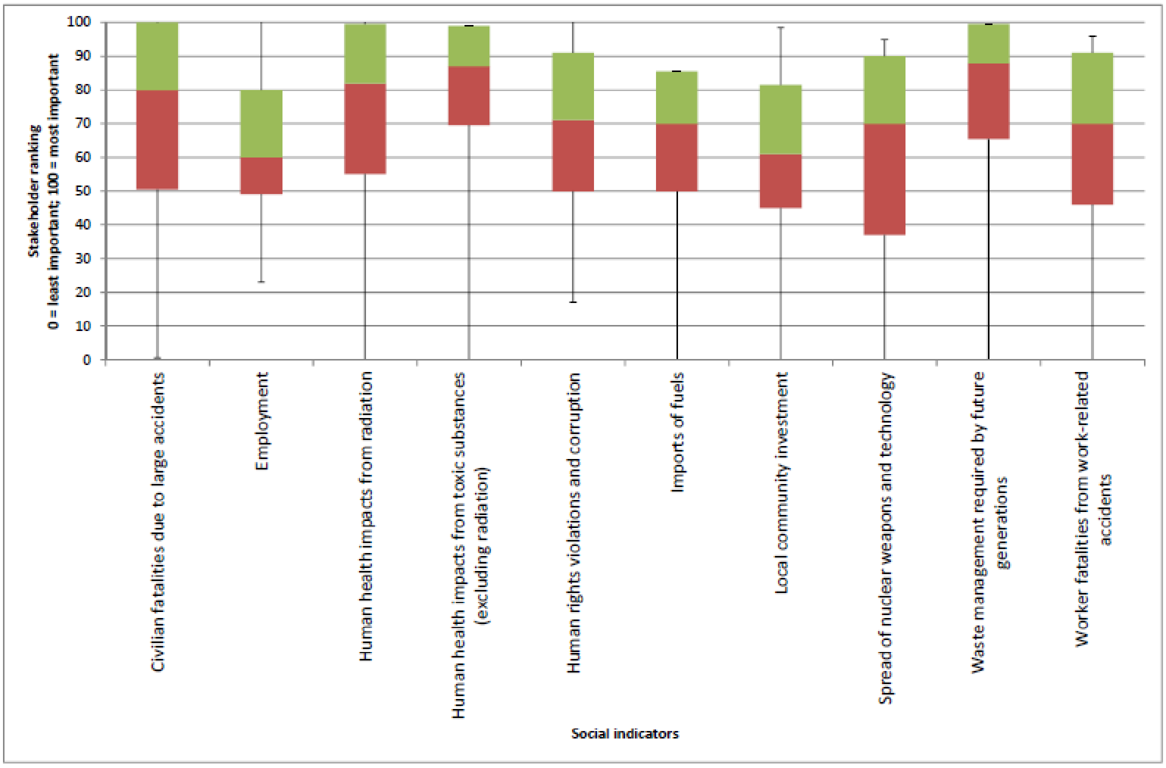


Figure 5.17. Boxplot displaying the distribution of public rankings for the social sustainability indicators. [The green and red boxes meet at the median value, and each represent the second and third quartiles of the data.]

5.2.3.5.5 Multi-criteria perspectives on the sustainability aspects

Clustering analysis was carried out on public opinion on the importance of the sustainability indicators and the results of this are displayed in the ternary diagram in Figure 5.18, plotted using the Microsoft Excel tri-plot (Graham and Midgley, 2000). The values for the clustering analysis were calculated for each stakeholder by determining the average (mean) rating that each respondent gave to the techno-economic, environmental and social aspects of sustainability, based on ratings from the groups of indicators. The average scores were then normalised and the percentage leaning towards each of the three pillars of sustainability was calculated for each stakeholder.

Again, this analysis provides insight into whether members of the public appear to form ‘groups’ based on their average ratings of each set of sustainability indicators. Averaging the indicators over each aspect of sustainability tends to give central values across the three groups, largely because respondents found some indicators within each group very important, whilst others were rated as much less important. The mean values show that the tendency is a central one, with outliers tending towards the techno-economic and environmental sustainability pillars. The results from the distribution analysis in the boxplots also supports this. The most dense clustering area on the ternary diagram below displays a leaning of around: 35% environmental, 33% social and 32% economic preference (the outliers towards techno-economic aspects raise the average rating of this aspect overall).

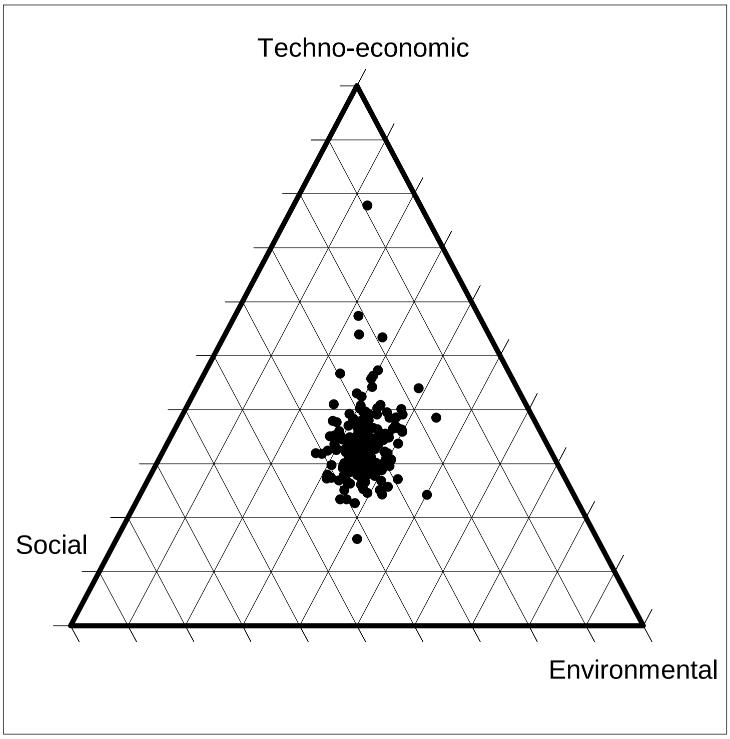


Figure 5.18. Distribution of public weights for the three pillars of sustainability generated from average indicator ratings.

Clustering analysis was also carried out on the AHP weights (for information on this MCDA method see section 2.4) which were derived from the public survey. Each respondent was asked which pillar of sustainability they considered to be the most important through use of the analytical hierarchy process. Pairwise comparisons were made across each pairs of sustainability indicators (environment compared to social, social compared to techno-economic and environmental compared to techno-economic) and respondents specified the extent to which one aspect was preferred above the other on ordinal scale of 1-9 (1 = equally important; 3 = slightly more important; 5 = strongly more important; 7 = very strongly more important; 9 = extremely more important; and values of 2, 4, 6 and 8 are used where compromise is needed). The eigenvectors were then calculated for each stakeholder's ratings for each sustainability aspect (this is done by multiplication of each of the entries from a single stakeholder and then taking the nth root of the product – the nth roots for each comparison are then summed which allows normalisation of the eigenvector values). And finally, the percentage leaning towards each sustainability aspect is then calculated to feed into the Tri-plot (Graham and Midgley, 2000) spread sheet. The results from these calculations can be seen in Figure 5.19, below.

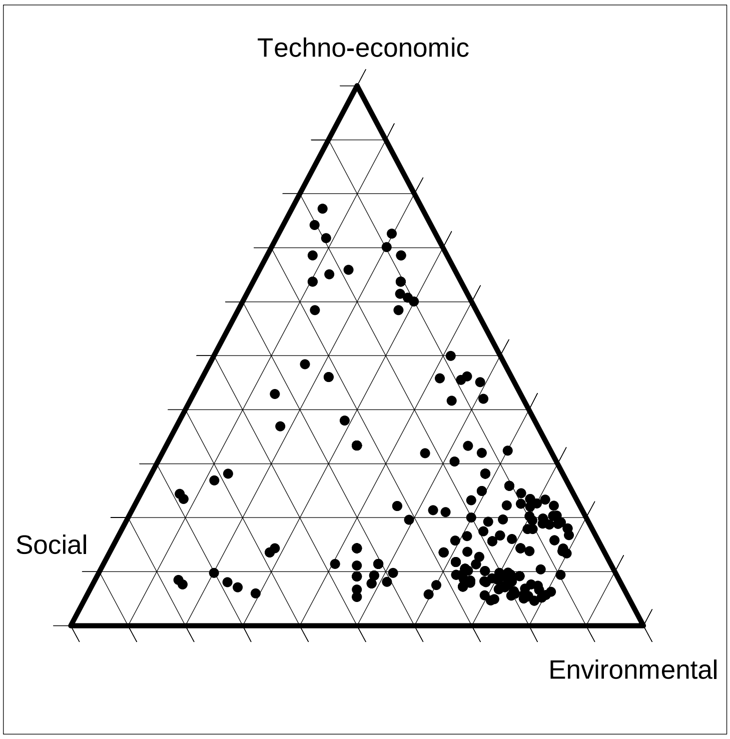


Figure 5.19. Distribution of public weights for the three pillars of sustainability based on AHP values.

From the ternary diagram displaying the range of AHP stakeholder preference for the importance of the sustainability impacts, it can be observed that the distribution of preference is much greater than those calculated from the average stakeholder ratings for the sustainability indicators. The majority of the results are plotted with an emphasis on environmental importance, with techno-economic second in overall importance and followed closely by social sustainability. On average, the leaning is 34.5% environmental, 3.1% techno-economic and 32.3% social. These results are in contrast to the average rating of the indicators displayed in Figure 5.18 in terms of extremity of opinion on the sustainability aspects. As with the ternary diagrams developed for expert opinion, the public opinion also differs when comparing rating of the indicators within the sustainability categories, compared to direct weighting of the sustainability aspects against each other.

5.2.4 Comparison of the expert and public opinion on sustainability indicators and electricity technologies

The findings from the first expert consultation helped identify sustainability issues which to present to the public in the first of the public surveys carried out. The first expert survey identified lifetime of global fuel reserves, greenhouse gas emissions and radioactive waste production as the top three most important issues to consider when assessing the sustainability of electricity options. Conversely, the first public survey identified water contamination, land contamination and then greenhouse gas emissions as the most important issues, which is largely different to the expert feedback. Only greenhouse gas emissions were identified by both groups as one of the most important issues.

The second expert and public surveys showed that both stakeholder groups favoured renewable electricity technologies out of those considered. The expert group rate hydroelectric power as the most favourable option overall, followed by solar and then wind power, whilst the public group considered solar and wind power (in that order) as the most favourable electricity options. There was also agreement on the most unfavourable electricity technologies between both stakeholder groups – expert and public stakeholders rated oil-fired power as the most unfavourable option, followed by coal- and gas-fired power. The most controversial electricity options varied somewhat between both stakeholder groups. Within the expert groups, the least consensus was reached on the opinion on coal-fired, gas-fired and nuclear power, whilst in the public group the most controversial options were nuclear and solar power. In the case of both stakeholder groups, both the public and experts displayed agreement on the unfavourability of oil-fired power.

The biggest difference between the expert views and public views is on the importance of the sustainability aspects (techno-economic, environmental and social), with the experts, overall, rating the techno-economic indicators as the most important to consider in a sustainability assessment of electricity options, whilst the public believed that environmental factors were the most important.

5.2.5 Summary of the second stage public consultation

The most favourable electricity options in the second-stage public survey were found to be solar and then wind power. The most unfavourable options were considered to be oil-, coal- and gas-fired power. The most controversial options amongst stakeholders that displayed least agreement on their favourability were nuclear and solar power. Most consensus was reached on the disapproval of oil-fired power.

The public rated the environmental indicators as the most important and these indicators had the highest average rating, followed by the techno-economic indicators. On average, the social indicators were considered the least important. Global warming was identified by most respondents as a very important issue. The most controversial set was the social set of indicators and the least controversial set of indicators was the environmental set, which displayed least distribution. This analysis identifies particularly contentious issues and divergence in public opinion on sustainability issues and electricity-generating technologies. Additionally, the indicators where consensus is reached and there is likely to be little divergence in opinion have also been identified.

These findings allow a full multi-criteria analysis model to be built in order to model public preferences and influence on electricity technology choice and specifically nuclear power decisions for the UK energy mix. In addition, several further issues on the current nuclear power programme and future for nuclear power in the UK are identified, with the majority of the respondents opposing further expansion of the UK's nuclear power programme.

This research is followed up in chapter 8 of this thesis, where future electricity scenarios are modelled using a variety of stakeholder perspectives (expert and public) in order to explore how expert decisions can affect decisions made on energy policy.

6 Application of the IAEA Indicators for Nuclear Power Development to Nuclear Power Generation in the UK

6.1 Introduction

Nuclear power is increasingly being turned to by nations to play a significant role in their future electricity supply. Nuclear power is a low carbon energy technology and can provide a relatively safe and reliable dynamic to a nation's energy mix (DECC, 2009). It is largely for these reasons that the nuclear energy debate and the adoption of a new generation of nuclear power stations have been thrust to the forefront of energy policy in many countries around the world.

Despite the numerous drivers for the development or expansion of nuclear power, significant barriers to nuclear power may also exist and need to be assessed at the national-level. A national-level perspective will allow individual countries to assess the wider drivers and barriers for nuclear power and may therefore be used by policy-makers to assist in decision-making on this subject (see section 2.3).

To aid this decision-making, the IAEA are currently developing Indicators for Nuclear Power Development (INPD). The indicators take into account energy, economic, environmental, institutional and social perspectives of nuclear power implementation or expansion. The indicators are largely descriptive, with some quantitative measures. Use of the indicators is primarily aimed at developing countries or emerging economies who may currently be considering adding nuclear power into their energy mix. However, they can also be applied to developed countries.

With this in mind, the INPD indicators have been applied to the UK situation and the results used in order to assess the UK's readiness or ability to adopt a new generation of nuclear power. A critical evaluation of the value of the indicators in a UK specific decision-support framework is also provided. These indicators are used as a complimentary approach to the indicators developed within the SPRIng decision-support framework – they are relevant to the national-level assessments while the SPRIng indicators are more suited to technology-level assessments. Thus the former serve to provide a context for the latter.

Section 6.3 details the results of the INPD when applied to the UK. Prior to that, section 6.2 gives a brief overview of the INPD development and discusses application of the indicators to the UK specific conditions.

6.2 Background to the INDP Development

The IAEA's Indicators for Nuclear Power Development (INPD) have primarily been developed due to the increased interest of many developing nations in implementing their own nuclear power programmes. A nuclear-specific, national-level perspective is needed in the nuclear case due to the demands that nuclear power may place on a country's economy, political and energy system structure, environment, institutions and society. These demands incorporate many sustainability issues, which the IAEA have identified as part of their INPD. The idea of the INPD is to assess a nation's situation in terms of these sustainability issues, taking into account the past trends that have led to their current position. The indicators are largely policy-related.

The IAEA has previously also developed other indicators for energy system planning and nuclear energy system analysis which include:

- UN Indicators for Sustainable Development
- Energy Indicators for Sustainable Development (IAEA, UN, IEA, EEA, Eurostat)
- Related indicator sets: *energy security indicators* (ECN), *knowledge indicators* (NKM), *technology specific sustainability indicators* (PSI)

The INPD's development has followed on from the creation of the above indicators sets. The full set of indicators can be seen in Table 6.1 and Table 6.2. The INPD have incorporated many indicators and aspects from the above sets. The novel aspect of the INPD is their nuclear-specific focus. Therefore, through use of the tried and tested indicator methods in the above-mentioned indicator sets combined with a nuclear angle, the INPD are a comprehensive, rounded and holistic approach in their assessment of nuclear energy implementation or expansion. The INPD provide a nuclear-specific focus when considering expanding or implementing a nuclear power programme and combine this focus with the knowledge gained from the IAEA’s previously developed indicator sets.

Table 6.1. List of the IAEA's INPD, detailing the energy, economy and environment themes.

Theme	Subtheme	Issue	Code	Indicator	Components
Energy	Use and production patterns	Policy	En1	Expected growth in primary energy supply and fuel mix for power generation	– Current and expected electricity generation capacity – Current and expected primary energy supply – Current and expected fuel mix for power generation, including nuclear power
		Energy diversification	En2	Non-carbon energy share in electricity and primary energy mix	– Non-carbon primary energy supply, – Total primary energy supply, – Non-carbon electricity generation and generation capacity – Total electricity generation and generation capacity
	Energy security	Imports	En3	Net energy import dependency	– Energy imports (by fuel and country of origin) – Total primary energy supply
		Access to fuel stocks/supplies	En4	Access to fuel cycle facilities	– Mining, Milling, Conversion, Enrichment, Fuel Fabrication, Nuclear Power Plant, Reprocessing, Intermediate Fuel Storage, High-level waste final disposal [0: not exist or not planned; 1: exist, planned or agreement with other country]
	Technology	Grid size	En5	Maximum unit size viable in the electric grid	– Electric grid size [GW]
Economy	Macroeconomy	Growth experience	Eco1	Past and expected growth in GDP	– Annual average growth in GDP (real terms) in the last five years (GDP per capita) – Expected annual average growth in GDP in next five years (GDP per capita)
		Vulnerability	Eco2	Balance of Trade	– Trade balance in last five years – Gross Fiscal Deficit (% of GDP)
	Financial markets	Access to finance	Eco3	Current Account Balance	– Current Account Balance over the last five years
		Capital markets	Eco4	Size of Capital Market	– Size of capital market [local currency]
Environment	Atmosphere	Climate Change	Ev1	GHG emissions from energy production and use per capita and per unit of GDP	– Current and expected fuel mix for power generation, including nuclear power
	Land	Solid Waste Generation and Management	Ev2	Ratio of solid radioactive waste and toxic waste to units of energy produced	– Amount of radioactive waste (cumulative for a selected period of time) – Energy produced
		Land availability and quality	Ev3	Land availability and quality	– Average power density of national energy system [W/m^2 land used] – Average population density [people/m^2] – Potential capacity of suitable sites available that are geologically stable for waste storage – Area of sites available for nuclear power plants that are seismically stable
	Other	Other environmental impact	Ev4	Life cycle impact of nuclear power and competing technologies: ecotoxicity, acidification, eutrophication, etc.	– Total national external costs of the electricity generation (c/kWh) – External costs of nuclear power generation (life cycle estimates) – External costs of competing technologies (coal, gas, wind, hydro)

Table 6.2. List of the IAEA's INPD, detailing the institutions and social and political themes.

Theme	Subtheme	Issue	Code	Indicator	Components
Institutions	Governance	Rule of law	In1	Rule of law index	– National source (or one dimension of the World Bank's Worldwide Governance Indicators)
		Political stability and absence of violence	In2	Political stability and absence of violence index	– National source (or one dimension of the World Bank's Worldwide Governance Indicators)
	Human resources	Technical education level	In3	Human skills	– Gross enrolment ratio at tertiary level in science, mathematics and engineering
	Institutional capacity	Nuclear development organization	In4	Budget and quality of human resources of nuclear development organization	– Budget and number of personnel of nuclear development organization – Quality of human resources for pre-project activities, project execution, O&M, etc. (subjective rating)
		Regulatory organizations	In5	Budget and quality of human resources of organizations responsible for nuclear regulation, electricity, health and environmental regulation	– Budget and number of personnel of the organizations – Quality of human resources (subjective rating)
	Human resources	Specific skills for nuclear	In6	Skilled technical manpower to manage, operate, maintain, and regulate a nuclear energy program	– Number of skilled technical people available to manage, operate, maintain, and regulate a nuclear energy program (persons).
Social and Political	Health	Industrial and Civilian Safety	Soc3	Industrial & Civilian Safety index	– Accident fatalities per energy produced by fuel chain [per GWh] – Industrial accidents at nuclear power plants [per 200,000 person-hours worked] – Population exposure to radiation from nuclear power station discharges compared to major competing technologies (e.g., coal power plants) [tU ot tTh per GWe]
	Public Acceptance	Social Risk	Soc6	Public acceptance index	– Approval rating of nuclear power in per cent, from national survey - Acceptance/Rejection limit – Growing pressure from public/stakeholders [energy affects economy and environment (public health, pollution, safety)]
	Political support/patronage	Government political support	Soc7	Government's expressed intention to develop nuclear energy	– Energy plan includes government actions to develop nuclear power (budget and personnel committed) – Government's position toward nuclear power (subjective rating)
	International cooperation	International agreements and conventions	Soc8	– Party to the NPT and comprehensive safeguards agreement – Intergovernmental agreements and protocols (including maritime airspace etc) – Conventions on nuclear safety – Convention on physical protection of nuclear material (CPPNM)	– Years in which country became party to the NPT and in which it concluded a comprehensive safeguards agreement – Years in which country become signatories of relevant agreements and protocols – Checklist on compliance

6.3 Application of INPD to the UK

In the following section, the results of the INPD applied to the UK situation are presented. The section is split into five subsections detailing the indicators within the main sustainability themes identified by INPD: energy, economy, environment, institutions and social & political.

Within each main theme, the individual indicators are presented and discussed. The work describes and analyses the UK's conditions in 2011, here considered as the base year (due to data availability). The trends that have led to the current condition and how policy might affect these conditions in the future are also considered. The data have been collected (in most cases and where possible) from UK government publications and sources.

There is no specific methodology provided with the INPD detailing how they should be applied. Instead, the IAEA's Energy Indicators for Sustainable Development: Guidelines and Methodologies (IAEA *et al.*, 2005) procedure has been followed in this work. In this way, the following are identified as objectives to be met by this part of the research (IAEA *et al.*, 2005):

- to clarify statistical information;
- to monitor the progress of past energy-related policies; and
- to provide a reality check on policy proposals.

6.3.1 Energy

The energy theme of the INPD contains three subthemes: use and production patterns, energy security and technology that capture issues such as energy supply growth and non-carbon electricity proportion of total energy and electricity.

6.3.1.1 Subtheme: use and production patterns

En1: Policy - Expected growth in primary energy supply and fuel mix for power generation

- *Component 1: Current and expected electricity generation capacity*

The UK supplied 374 TWh of electricity in 2011 (DECC, 2012d). Electricity supply in 2011 consisted of: gas-fired stations (40%), coal-fired power stations (30%), nuclear power stations (19%), renewables (9.4%) and the remainder from other sources (2.5%).

The UK government acknowledged in their energy review paper, ‘The Energy Challenge’ (DTI, 2006b) that 25 GW more capacity would need to be built by 2025 to meet increasing demand and to replace closing coal and nuclear power stations. 25 GW equates to around 30% existing capacity (DTI, 2006b). As part of their energy review in 2006, the Department for Trade and Industry (DTI) made a projected electricity generation mix to 2020 (Figure 6.1). It can be seen from this figure that electricity generation from gas and renewables is expected to rise significantly, while nuclear’s contribution will fall significantly. Coal’s contribution will fall slightly, while oil, imports and pumped storage will remain roughly the same. Despite the projected fall in nuclear power contribution detailed in ‘The Energy Challenge’ (DTI, 2006b), nuclear’s contribution is likely to rise under current government plans for expansion of the UK’s nuclear power programme. However, due to the length of the planning process and construction times, many of the new nuclear power plants are likely to start generating electricity after these 2020 energy projections.

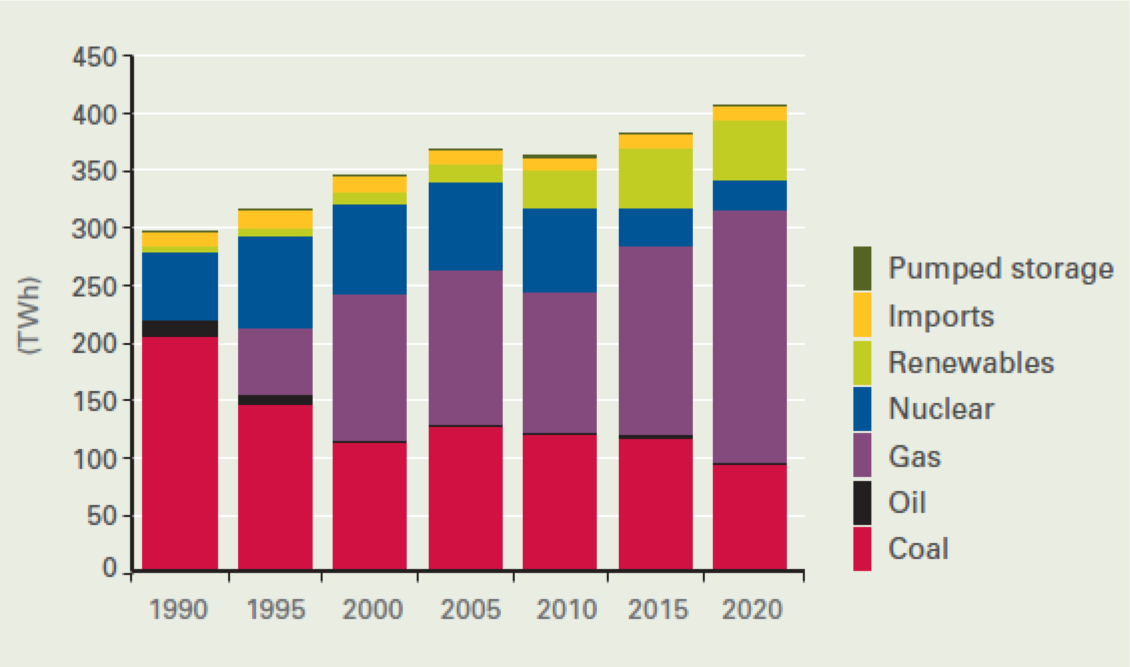


Figure 6.1 Projected electricity generation capacity for the UK (DTI, 2006b).

- *Component 2: Current and expected primary energy supply*

The current (2011) primary energy supply (production) for the UK is: natural gas (45 Mtoe), petroleum (57 Mtoe), coal (11 Mtoe), and primary electricity (17 Mtoe) (DECC, 2012d). This is a total of 130 Mtoe. The total consumption (demand) for 2011 was 204 Mtoe, meaning the deficit in supply (74 Mtoe) was made up by foreign trade, marine bunkers and stock changes (DECC, 2012d).

In 2008, the government updated their energy and carbon emissions projections from the Energy White paper produced in 2007 by the DTI (DTI, 2007). Figure 6.2 projects the relative changes in contribution to primary energy demand. As it can be seen, these projections have been made based on an assumption that the White Paper policies are followed through and that the future price of fossil fuels remains central to the government's projections.

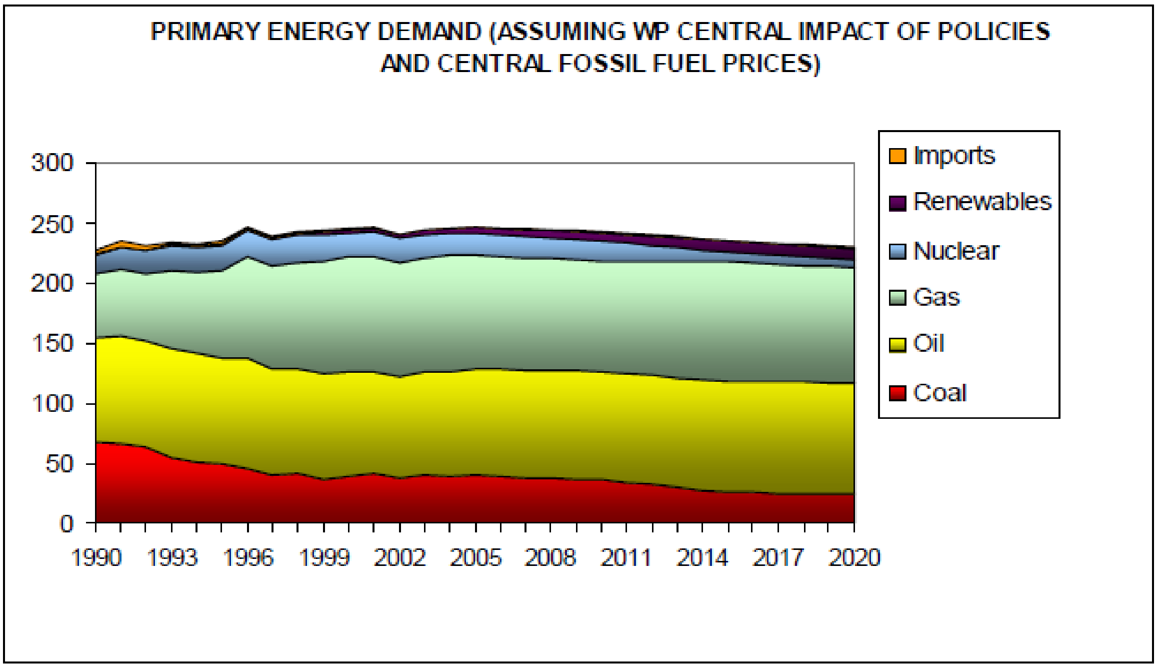
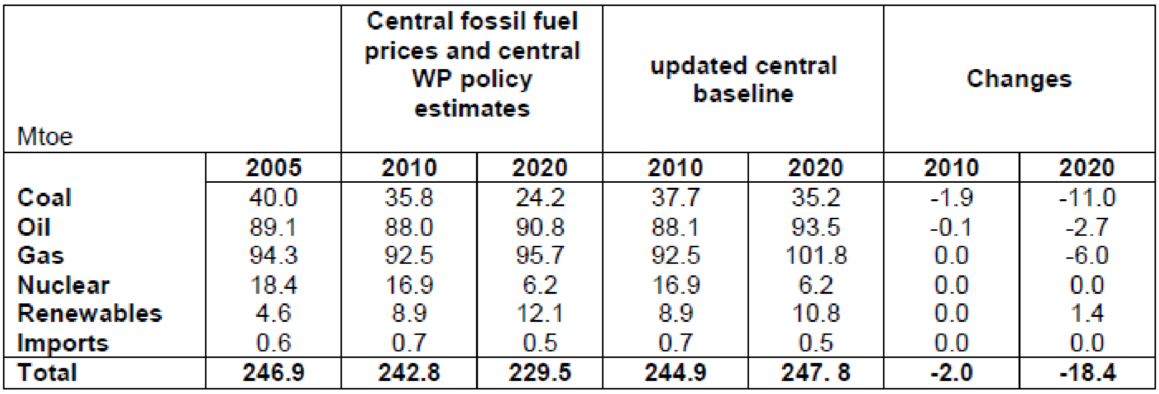


Figure 6.2 Historic and projected primary energy demand assuming impacts of White Paper (2007) policies and central fossil fuel prices (DTI, 2007).

Table 6.3 shows projected figures from the contributing primary energy technologies following central fossil fuel prices from White Paper (2007) policy estimates and baseline estimates from 2005 figures. It can be seen from these projections that contributions from coal and nuclear are set to decrease under White Paper (2007) policies from 40 Mtoe (2005) to 24.2 Mtoe (2020) and 18.4 Mtoe (2005) to 6.2 Mtoe (2020) respectively. Renewables are set to make the largest increase in contribution to primary energy, from 4.6 Mtoe (2005) to 12.1 Mtoe in 2020. Gas is projected to increase its contribution slightly (94.3 Mtoe in 2005 to 95.7 Mtoe in 2020), whilst contributions from oil and imports will remain approximately the same. As stated earlier under component one of this indicator, the decrease in contribution from nuclear in these projections (despite the government advocating the advancement of the UK's nuclear power programme), could be attributed to the time taken to implement new nuclear power stations (i.e. construction of the plants and generation from them will probably occur after the projections detailed in Table 6.3).

Table 6.3 Primary energy demand by fuel in 2010 and 2020, following White paper (2007) impacts and baseline estimates (from 2005) (DTI, 2007).



Mtoe		Central fossil fuel prices and central WP policy estimates		updated central baseline		Changes	
	2005	**2010**	**2020**	**2010**	**2020**	**2010**	**2020**
Coal	40.0	35.8	24.2	37.7	35.2	-1.9	-11.0
Oil	89.1	88.0	90.8	88.1	93.5	-0.1	-2.7
Gas	94.3	92.5	95.7	92.5	101.8	0.0	-6.0
Nuclear	18.4	16.9	6.2	16.9	6.2	0.0	0.0
Renewables	4.6	8.9	12.1	8.9	10.8	0.0	1.4
Imports	0.6	0.7	0.5	0.7	0.5	0.0	0.0
Total	**246.9**	**242.8**	**229.5**	**244.9**	**247. 8**	**-2.0**	**-18.4**

- *Component 3: Current and expected fuel mix for power generation, including nuclear power*

The Digest of UK Energy Statistics (DUKES) provides annual data for fuel used for energy generation (DECC, 2012d). Coal, oil and gas are displayed in their original units of measurements and million tonnes of oil equivalent, whilst nuclear fuel is expressed only in million tonnes of oil equivalent. The fuel mix used for power generation in 2011 is displayed below in Table 6.4.

Table 6.4 Fuel used in power generation from in the year 2011 for the UK (DECC, 2012d).

Major Power Producers	Unit	Year: 2011
Coal	M tonnes	40.57
Oil	M tonnes	0.29
Gas	GWh	275 591
Coal	Mtoe	25.232
Oil	Mtoe	0.346
Gas	Mtoe	23.697
Nuclear	Mtoe	15.626
Total fuel used	Mtoe	64.901

The Carbon Plan (DECC, 2011) makes projections for the UK electricity mix to 2050, specifying which low carbon electricity technologies and the amounts of these technologies needed in order for the UK to meet its carbon targets. DECC specify high and low uptakes of the three types of electricity technology, with nuclear power between 16 – 76 GW, CCS between 1 – 41 GW, and renewable capacity between 20 – 107 GW. Electricity demand is set to rise to between 30-60% of current capacity and DECC aim to have almost eliminated carbon emissions from the power sector by 2050, by large-scale implementation of the above technologies.

Table 6.5 below also displays projections for fuel use in 2020 for power generation, based on the changes in power demand projected by DTI (2006b) outlined under energy indicator En1, above. It is assumed that 100% of nuclear fuel is used for power generation. For coal, it is assumed that in 2020 power generation from coal-fired power plants will be 79% of 2011's value. For gas, it is assumed that electricity generation from gas-fired power stations will be 180% of 2011's value, and for oil it is assumed that power generation from this method remains the same as in 2011 (100%). This is based on projections from DTI, 2006.

Table 6.5 Total projected fuel use for power generation in the year 2020 for the UK (based on DTI, 2006b).

Major Power Producers	Power Generated (2011)	Fuel Used for Power Generation (2011)	Projected Primary Energy Demand (2020)	Change in Power Generation	Fuel Use for Power Generation (2020)
Coal	25.2 Mtoe	40.57 M tonnes	24.2 Mtoe	79% less	32.1 M tonnes
Oil	0.34 Mtoe	0.29 M tonnes	90.8 Mtoe	Remains same	0.29 M tonnes
Gas	23.7 Mtoe	275 591 GWh	95.7 Mtoe	80% more	496 063
Nuclear	15.6 Mtoe	181 732 GWh	6.2 Mtoe	69% less	72 693 GWh

<u>En2: Energy Diversification - Non-carbon energy share in electricity and primary energy mix</u>

- *Component 1: Non-carbon primary energy supply*

Under the INPD, there is no specific definition for 'non-carbon' primary energy or energy technology. For the purposes of this work, 'non-carbon' energy will be interpreted as those technologies which are classed as ‘low carbon’. This includes all renewable technologies and nuclear power.

In 2011, a total of 7 457 thousand tonnes of oil equivalent (Ttoe) of primary energy came from bioenergy and waste (DECC, 2012d). Primary and secondary electricity contributed 364 897 GWh in 2011 (DECC, 2012d). Of this, 103 389 GWh are classed as low carbon (68 980 GWh nuclear, 5 686 GWh hydro, 15 750 GWh wind, and 12 973 GWh other renewables).

In total, 16.35 Mtoe (or 190 113 GWh) of primary energy supplied in 2011 are classed as low carbon which is equivalent to 7.7% of total energy supply.

- *Component 2: Total primary energy supply*

The total primary energy supply for the UK was 211.7 Mtoe (2 462 071 GWh) in 2011 (DECC, 2012d).

- *Component 3: Non-carbon electricity generation and generation capacity*

The total non-carbon, or low carbon electricity generation in the UK for 2011 was 103 389 GWh (DECC, 2012d).

- *Component 4: Total electricity generation and generation capacity*

The total electricity generation and generation capacity for the UK is 368 TWh (at a maximum load of 56 GW) and 89 GW respectively (DECC, 2012d).

6.3.1.2 Subtheme: energy security

<u>En3: Imports - Net energy import dependency</u>

- *Component 1: Energy imports (by fuel and country of origin)*

In 2011, the UK imported a total of 162 180 Ttoe (162 Mtoe) of energy (DECC, 2012d). The relative contributions by fuel type are listed in Table 6.6.

Table 6.6 Fuel imports into the UK in 2011 by fuel type and amount DECC, 2012d).

Fuel Type	**Amount Imported (Ttoe)**
Coal	21 399
Manufactured fuel	35
Primary oils	62 917
Petroleum products	24 942
Natural gas	50 251
Bioenergy & waste	1 890
Electricity	747

Research into the diversity of the UK's fuel supply mix has been carried out by Stamford and Azapagic (2012) and the results of this assessment are displayed below (Figure 6.3). Ukraine's precarious position in 2005 when their gas supply was closed off by Russia is evident from their placing on the diversity of fuel supply scale – the low diversity in supply left Ukraine very open to fuel shortages due to supplies being halted from a major supply country. The UK's supply of steam coal has been the least diverse of fuel imports for electricity generation in recent years. An increase of coal-fired power or coal CCS power could therefore leave the UK open to fuel shortages in the incidence of potential geopolitical conflicts.

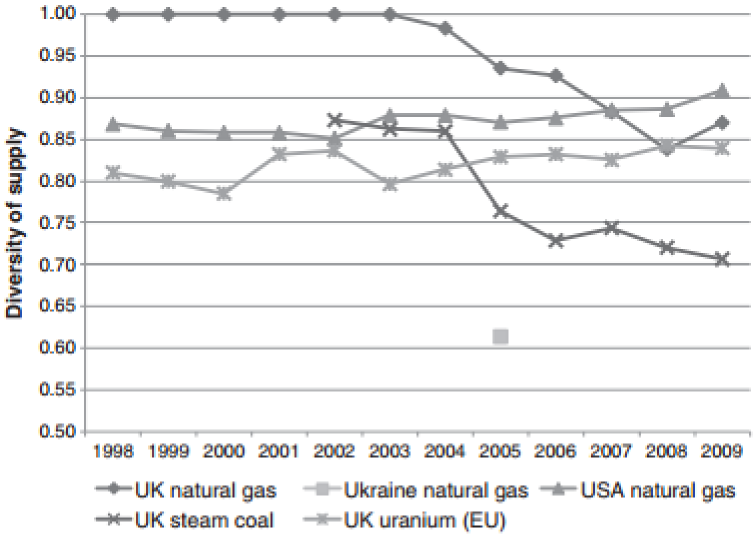


Figure 6.3. Historical diversity of fuel supply index for UK fuel imports used for electricity generation (Stamford and Azapagic, 2012).

- *Component 2: Total primary energy supply*

The total primary energy supply for the UK in 2011 was 211.7 Mtoe (DECC, 2012d). Therefore, the proportion of energy imported of overall consumption is 36.5% of total primary energy used in the UK (DECC, 2012d).

En4: Access to fuel stocks/supplies - Access to fuel cycle facilities

- *Component 1: Mining, milling, conversion, enrichment, fuel fabrication, nuclear power plant, reprocessing, intermediate fuel storage, high-level waste final disposal (0: not exist or not planned; 1: exist, planned, or agreement with other country)*

The UK has access to all of these parts of the nuclear life cycle except for the waste disposal and mining stage as there are no indigenous uranium deposits in the UK.

6.3.1.3 Subtheme: technology

En5: Grid size - Maximum unit size viable in the electric grid

- *Component 1: Electric grid size (GW)*

The maximum capacity of the electricity grid in the UK in 2011 was 89 GW and the maximum load was 56 GW. Maximum demand was 63% of UK capacity (DECC, 2012b).

6.3.1.4 Discussion of energy indicators

The INPD's energy indicators provide a valuable insight into the UK's past energy provision, future targets and current situation with regard to its electricity infrastructure and nuclear life cycle supply chain.

Energy policy in the UK has identified 25 GW of increased power capacity needs to be built by 2025. Policy has suggested that this increase in provision should be provided primarily by an increase in natural gas power station and renewables. In 2011, the Government announced a £7 billion investment in low carbon technologies in 2011, to boost these technologies significantly (The Telegraph, 2011). Primary energy demand projections suggest that consumption of primary energy will fall. This view is upheld by the projected future fuel mix (Figure 6.1) where, in 2020 nuclear fuel is expected to be a third of its 2005 level (DTI, 206b). However, a large amount of nuclear capacity will come offline over the next 15 years as many nuclear power stations reach the end of their working lives. The earliest new nuclear reactor had been predicted to be generating electricity and feeding into the UK grid by late 2017, although this is now likely to be delayed beyond this date (WNN, 2012). This indicates that a large increase in the capacity of nuclear power in the UK will take place beyond, or after the government has projected the increases in nuclear power contribution, due to the time taken for the planning and construction of nuclear power plants.

The Energy Diversification indicators show that together with nuclear power, low carbon technologies account for a much larger proportion of low carbon energy than without it. Around a quarter of primary and secondary electricity came from low carbon technologies in 2011. Of this, nuclear power makes up around 66.7%.

A significant proportion (36.5%) of the UK's energy comes from imports meaning that the UK is heavily reliant on foreign relations with countries that it gets its energy from. Further investigation of the countries involved in importing energy to the UK will allow the sensitivity of these relations to be analysed in order to determine the UK's energy vulnerability to any future international disputes.

On a related note, the UK has in place facilities, or agreements with other countries on all but two of the nuclear fuel cycle stages (mining/access to uranium and high-level waste final disposal). Therefore, international disputes may make the UK vulnerable in terms of access to the life cycle stages of nuclear power generation. For example, access to uranium might be restricted in the future.

Regarding waste disposal, it is likely that sites in the UK will be chosen. However, in the mean-time, the lack of repository opens up the nuclear debate to further criticism from stakeholders and increases the cost of final disposal due to the prolonged consultation and deliberation on this contentious issue.

Finally, the indicator related to the grid infrastructure shows that the maximum capacity of the UK grid is 89 GW, and maximum demand so far has been 56 GW. With a projected addition of 25 GW more capacity by 2025, the UK grid will need updating and expanding, which is not a trivial task and is likely to increase electricity prices.

6.3.2 Economy

The economy theme of the INPD contains two subthemes: macro-economy and financial markets, which capture economic growth within a nation as well as its ability to finance nuclear power programmes and economic vulnerability.

6.3.2.1 Subtheme: macro-economy

Eco1: Growth experience - Past and expected growth in GDP

- *Component 1: Annual average growth in GDP (real terms) in last five years (GDP per capita)*

The annual average GDP growth (GDP/population) over the past five years for the UK has been as given in Table 6.7.

Table 6.7 Annual average GDP growth for the UK over the last five years (IMF, 2012 Oct).

Year	**GDP Growth (pounds)**
2011	22 953(£)
2010	22 935(£)
2009	22 684(£)
2008	23 787(£)
2007	24 1768(£)

- *Component 2: Expected annual average growth in GDP in next five years (GDP per capita)*

The expected average GDP growth (GDP/population) for the UK is expected to be as follows (IMF, 2012 Oct):

Table 6.8 Annual average GDP growth for the UK expected over the next five years.

Year	**GDP Growth (pounds)**
2012	22 713(£)
2013	22 814(£)
2014	23 159(£)
2015	23 598(£)
2016	24 040(£)

Eco2: Vulnerability - Balance of trade

- *Component 1: Trade balance in last five years*

The trade balance over the last five years for the UK has been as follows (ONS, 2012 Oct):

Table 6.9 Trade balance for the UK over the last five years.

Year	Trade Balance (pounds)
2012	-£2 500 million
2011	-£4 250 million
2010	-£3 500 million
2009	-£2 050 million
2008	-£2 800 million

- *Component 2: Gross fiscal deficit (% of GDP)*

The gross fiscal deficit for the UK has been as follows (ONS, 2012 Sept):

Table 6.10 Gross fiscal deficit for the UK over the last five years.

Year	Gross Fiscal Deficit
2012	7.7%
2011	9.6%
2010	11.5%
2009	7%
2008	2.8%

6.3.2.2 Subtheme: financial markets

Eco3: Access to finance - Current account balance

- *Component 1: Current account balance over the last five years*

The UK's current account balance over the last five years (IMF, 2012 Oct):

Table 6.11. Current account balance of the UK over the last five years.

Year	Current Account Balance (dollars)
2012	-39 billion($) (-1.6% GDP)
2011	-37 billion($) (-1.6% GDP)
2010	-75 billion($) (-1.7% GDP)
2009	-29 billion($) (-1.3% GDP)
2008	-41 billion($) (-1.5% GDP)

Eco4: Capital markets - Size of capital market

- *Component 1: Size of capital market (local currency)*

The size of capital market in the UK is not currently available in the public domain, as far as the author is aware.

6.3.2.3 Discussion of economic indicators

The economic indicators in this section allow a top-level assessment of the UK's economic trends and access to finance to support a nuclear power programme.

The 'growth experience' indicators display a growth in the UK's GDP in the past five years and growth in GDP is also projected over the next five years to 2016. Although GDP has risen over the last two years, the increase in value of GDP over each year has increased at: 0.7% (2011) and 2.1% (2010) (The World Bank, 2012) – the recovery from recession is predicted to be long and slow.

The UK's economic vulnerability has been defined by the Balance of Trade indicator, which incorporates trade balance and gross fiscal deficit. The UK's balance of trade has been focussed unfavourably on imports, which has led to an overall deficit of trade balance. In addition to the increase gross fiscal deficit has left the UK vulnerable to potential insolvency. Access to finance has also been severely limited due to the UK's current account debt of -39 billion dollars in 2012. This indicates that the UK's net foreign assets are in deficit. Reducing current account debt often means that governments will try to increase exports and become less reliant on imports from other nations.

These trends of the economic indicators may predict unwillingness from government to finance new nuclear power programmes, which is realised in the government's commitment the nuclear power without subsidies (BBC, 2010 July; WNN, 2010).

6.3.3 Environment

The environment theme of the INPD contains three subthemes: atmosphere, land and other. Issues such as climate change, waste management, land availability and quality and other life cycle impacts of competing technologies are addressed.

6.3.3.1 Subtheme: atmosphere

Ev1: Climate change - GHG emissions from energy production and use per capita and per unit of GDP

- *Component 1: GHG emissions from energy production and use*

The total GHG emissions in the UK for 2011 was 549.3 million tonnes CO_2 eq. (DECC, 2012e). GHG emissions by source and end user for 2011 are as shown in Figure 6.4.

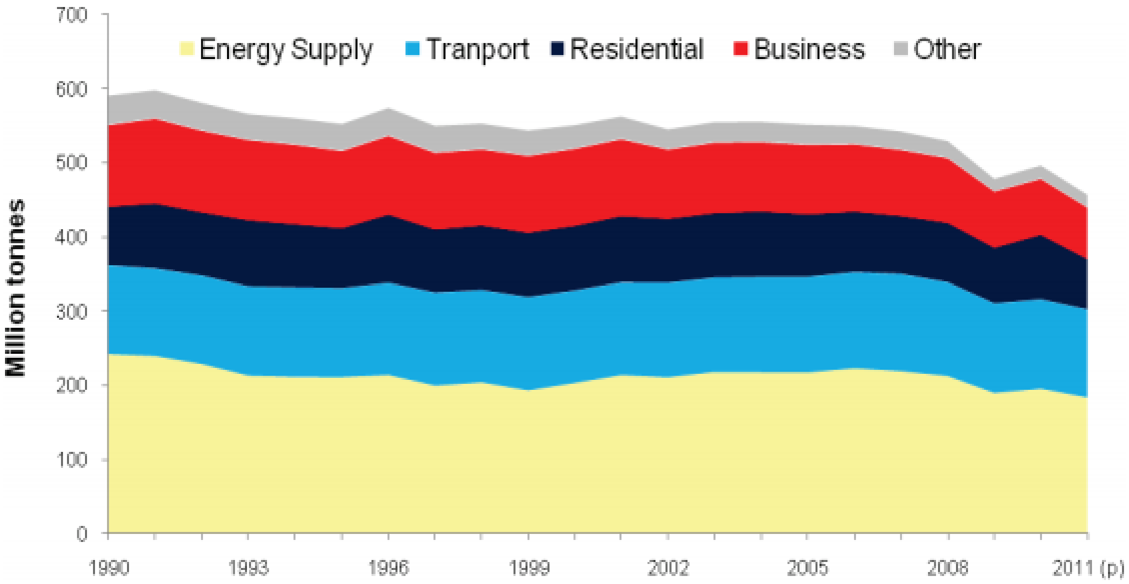


Figure 6.4 Graph showing GHG emissions for the UK in 2011 by source and end user (DECC, 2012e).

6.3.3.2 Subtheme: land

Ev2: Solid waste generation and management - Ratio of solid radioactive waste and toxic waste to units of energy produced

- *Component 1: Amount of radioactive waste (cumulative for a selected period of time)*

The amount of radioactive waste in the UK (NDA, 2011):

- HLW = 1 000 m^3
- ILW = 290 000 m^3
- LLW = 4 400 000 m^3

This waste has accumulated over 55 years.

Ev3: Land availability and quality - Land availability and quality

- *Component 1: Average power density of national energy system [W/m^2 land used]*

The installed capacity in the UK is 86 998 MW (DECC, 2012d). Therefore, the average power density of the national energy system (W/m^2) = 0.36 (Nigeria has a power density of 0.008 W/m^2). Dividing the power density by the population density (see below) gives a value of 1385 W/person, compared to 5 W/person in Nigeria.

- *Component 2: Average population density [people/m^2]*

The population total of the UK = 62 644 000 (IMF, 2012 Oct) and the surface area of the UK is 242 900 km^2. Therefore, the average population density (people/m^2) = 0.00026 m^2.

- *Component 3: Potential capacity of suitable sites available that are geologically stable for waste storage*

Due to an ongoing review of potentially suitable sites that are available for waste storage in the UK, the capacity to store this waste is not yet known.

- *Component 4: Area of sites available for nuclear power plants that are seismically stable*

There is no information currently for this indicator. However, the whole of UK is considered to be relatively seismically stable.

6.3.3.3 Subtheme: other

Ev4: Other environmental impact - Life cycle impact of nuclear power and competing technologies: eco-toxicity, acidification, eutrophication, ozone depletion potential and photochemical smog potential

- *Component 1: Total national external costs of the electricity generation (c/kWh)*

The UK national total external costs of electricity generation are not currently known.

- *Component 2: External costs of nuclear power generation (life cycle estimates)*
- *Component 3: External costs of competing technologies (coal, gas, wind, hydro)*

As far as the author of this work is aware, the work carried out by Stamford and Azapagic (2012) is the only comparative assessment of the environmental life cycle assessment of electricity-generating technologies in the UK (which includes nuclear power). However, the ExternE project (IER, 2005) calculated the total external costs for a variety of electricity technologies specific to EU conditions. The results from the assessment by Stamford and Azapagic (2012) are displayed in Figure 6.5.

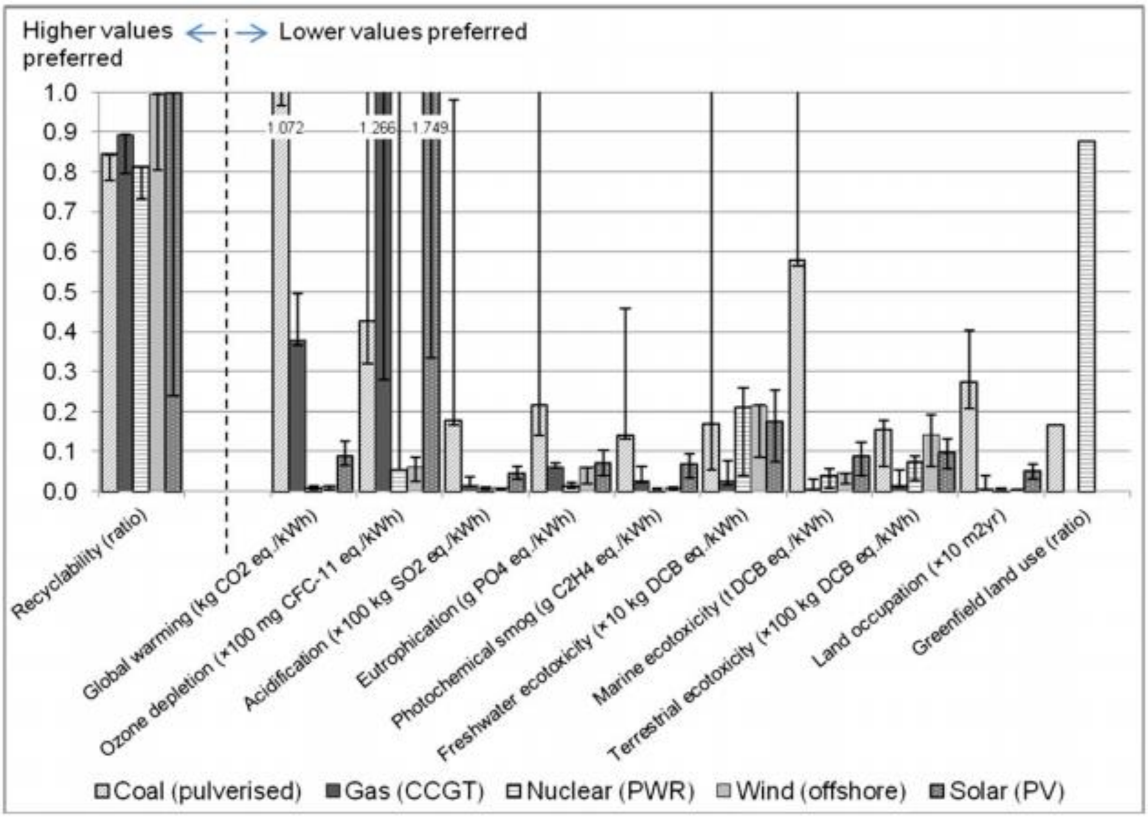


Figure 6.5. Life cycle environmental impacts of competing electricity technologies in a UK-specific context (Stamford and Azapagic, 2012).

6.3.3.4 *Discussion of environment indicators*

The INPD’s environment indicators provide detail under four subthemes: atmospheric impacts, land impacts and life cycle assessments of competing technologies compared to nuclear power.

Figure 6.4 shows that the energy sector was the largest single contributor to GHG emissions in 2011. This indicates that big reductions in this sector would make a large impact on the amount of greenhouse gases emitted into the atmosphere. Per capita GHG emissions from the energy sector in 2011 were around 3.19 tonnes (DECC, 2012e). The

GHG emissions for the energy sector per unit of GDP was 148 g CO_2-equivalent per £1 in 2011.

The UK is relatively densely populated compared to many other similar European and also non-European countries. This indicates that the UK has less area available for energy production and potentially less suitable sites for nuclear power generation and radioactive waste disposal.

Research that was carried out as part of the SPRIng project has contributed towards a comparison of the life cycle impacts of nuclear energy to other competing energy technologies (see Figure 6.5). The results show that some of the electricity-generating options have lower environmental impact than others, but there is not one electricity option that performs best under all of the environmental indicators. Therefore, discussion and trade-off of some of the indicators will be necessary in the implementation of national electricity policy.

6.3.4 Institutions

The institutions theme of the INPD contains four subthemes: governance, institutional capacity and two human resources subthemes, dealing with technical education levels and nuclear-specific skills.

6.3.4.1 Subtheme: governance

In1: Rule of law - Rule of law index

The rule of law indicator captures perceptions of the quality of public services and the civil service and the degree of a nation's independence from political pressures. It also captures the quality of policies formed and their implementation and the commitment government has to policies it introduces (WB, 2011).

- *Component 1: One dimension of the World Bank's Worldwide Governance Indicators*

The Worldwide Governance Indicators (WGI) are provided by the World Bank (WB) and give information on six dimensions related to governance for 212 countries (WB, 2011).

The indices are used to measure the following dimensions of governance: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption. The indicators are aggregate measures based on the views of enterprise, citizen and expert survey responses carried out in developed and developing countries.

Information from the World Bank's Rule of Law indicator places the UK (in 2011) at the 92.5 percentile rank (zero corresponds to the last and 100 to the highest rank). These indicators reflect governance at the country level and do not specifically relate to nuclear development.

In2: Political stability and absence of violence: Political stability and absence of violence index

The Political Stability and Absence of Violence indicator measures likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including politically-motivated violence and terrorism (WB, 2011).

- *Component 1: One dimension of the World Bank's Worldwide Governance Indicators*

Information from the World Bank's Political Stability and Absence of Violence indicator places the UK (in 2011) at the 60.4 percentile rank (zero corresponds to the last and 100 to the highest rank). For comparison, Finland measures 97.6 on this indicator, Spain 50.9 and Mexico 25.5. These indicators reflect governance at the country level and do not specifically relate to nuclear development.

6.3.4.2 Subtheme: human resources

In3: Technical education level: Human skills

- *Component: Gross enrolment ratio at tertiary level in science, mathematics and engineering*

The UN's Human Development Index comprises a number of indicators (life expectancy, education and GDP) and is calculated from an average of the indicators (UN, 2008). The gross enrolment ratio is one of these indicators and is a statistical measure of the level of education from primary to tertiary level. It is calculated by expressing the number of students from enrolled from primary to tertiary level as a percentage of the population of individuals of school age.

The UN's GER for tertiary level education in the UK is 57% (UN, 2008).

To calculate the GER in the UK of science, mathematics and engineering tertiary level students in the UK, the Office for national Statistics and Department for Education data, 'Post Compulsory Education' has been used (DfE, 2011 Nov). The number of students enrolled in full and part-time education (in science, maths and engineering) at tertiary level in the UK was 7.7% of total tertiary level enrolments for the UK in 2009/10. 7.7% of 59.2% (to work out the overall GER for tertiary education of science, maths, manufacturing and engineering in the UK) is therefore 4.56% GER.

6.3.4.3 Subtheme: institutional capacity

In4: Nuclear development organisation - Budget and quality of human resources of nuclear development organisation

- *Component 1: Budget and number of personnel of nuclear development organisation*

The budget for and number of human resources of the UK's nuclear development programme is not freely available.

- *Component 2: Quality of human resources for pre-project activities, project execution, O&M, etc. (subjective rating)*

Information is not readily available on the quality of human resources involved in the nuclear power programme in the UK. However, bodies such as The Royal Academy of Engineering and The Nuclear Industry Association have published reports regarding nuclear skills capacity for building the next generation of nuclear power plants in the UK (RAENG, 2010).

In5: Regulatory organisations - Budget and quality of human resources of organisations responsible for nuclear regulation, electricity, health and environmental regulation

- *Component 1: Budget and number of personnel of the organisations*

Information on the budget and number of personnel of the Health and Safety Executive's Nuclear Directorate and Environment Agency's nuclear division is not freely available.

- *Component 2: Quality of human resources (subjective rating)*

Information is not available on the quality of human resources of regulatory organisations involved in the nuclear power programme in the UK.

6.3.4.4 Subtheme: human resources

In6: Specific skills for nuclear - Skilled technical manpower to manage, operate, maintain, and regulate a nuclear energy program

- *Component: Number of skilled technical people available to manage, operate, maintain, and regulate a nuclear energy program (persons)*

Information on this indicator is not currently available.

6.3.4.5 Discussion of institutions indicators

The INPD institutions indicators describe the UK's situation in terms of it being able to effectively manage a nuclear power programme through governance, human resources and institutional capacity subthemes.

The extent to which the UK has an effective governance structure is defined by the Rule of Law and Political Stability and Absence of Violence indices. The UK scores highly on the rule of law indicator, with a 92.5 rank. For political stability the UK ranks at 60.4 per cent. The World Bank country specific reports on political stability show that the measure of this indicator has been in decreasing since the year 2000, when the UK ranked at 84%. This declining ranking is largely due to the likelihood of politically motivated terrorism since 2001. However, the UK is considered one of the most stable nations globally and therefore has an effective governance structure to operate and manage a nuclear power programme.

The Gross Enrolment Ratio at tertiary level is science, maths and engineering has been estimated at 4.56%. Although the UK has a relatively high GER for tertiary level education, the percentage penetration of these students studying science, maths and engineering is relatively low. A generation gap of nuclear scientists and engineers has been talked about in the UK in recent years due to the uncertainty in the nuclear power programme (RAENG, 2010). A deficiency of scientists and engineers is likely to exacerbate this problem as the proportion that would enter the nuclear sector would be fewer than if a greater proportion of tertiary-level students enrolled on science, maths and/or engineering courses.

The remaining institutions indicator data are not freely available or provided by the organisations that they seek to assess. Further investigation of these indicators and the organisations that hold the relevant data is be therefore needed.

6.3.5 Social and Political

The social and political theme of the INPD contains four subthemes: health, public acceptance, political support and international cooperation.

6.3.5.1 Subtheme: health

Soc3: Industrial and civilian safety: Industrial and civilian safety index

- *Component 1: Accident fatalities per energy produced by fuel chain (per GWh)*

Comparative data on this indicator are not readily available that are specific only to the UK. However, the Paul Scherrer Institut's (PSI) Technology Assessment group has conducted extensive research on risk assessment, including aggregated data on severe energy fatalities across the fuel chains (including coal, oil, natural gas, LPG, hydro and nuclear technologies). Figure 6.6 displays historical severe accident fatalities (1969-2000 apart from the China Coal Industry Yearbook) for OECD countries, EU countries, non-OECD (without China), non-OECD (with China), China and China 1994-1999 (PSI, 2006 Feb). The results are displayed in fatalities per GW-Yr. These results clearly show that nuclear has had the least number of fatalities from severe accidents in OECD, EU and non-OECD countries in the years from 1969-2000.

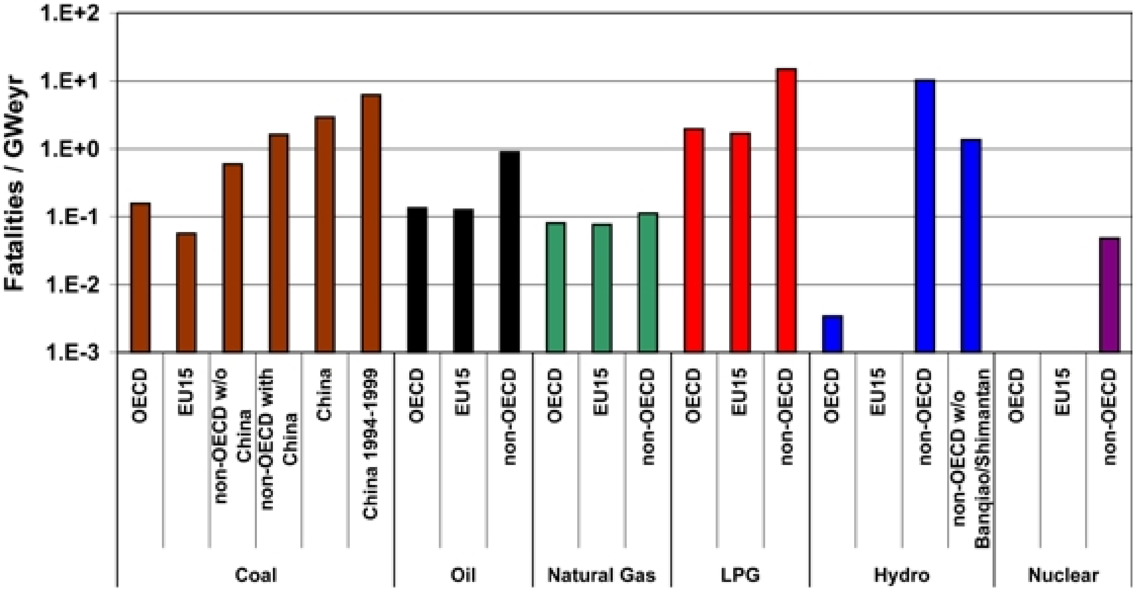


Figure 6.6 Graph comparing the aggregated and normalised energy-chain related fatalities per GW-Yr (PSI, 2006).

- *Component 2: Industrial accidents at nuclear power plants (per 200, 000 person-hours worked)*

Information on this indicator is not currently available.

- *Component 3: Population exposure to radiation from nuclear power station discharges compared to major competing technologies (e.g. coal power plants) [tU ot tTh per GWe)*

The population exposure of radiation has been calculated to be 0.02 DALY/GWh (see Chapter 7, section Figure 7.3). The equivalent impact for coal power plants is 0.00049 DALY/GWh and coal CCS is 0.00052 DALY/GWh.

6.3.5.2 Subtheme: public acceptance index

<u>Soc6: Social risk: Public acceptance index</u>

- *Component 1: Approval rating of nuclear power in per cent, from national survey – acceptance/rejection limit*

The Nuclear Energy Agency in 2010 published a report on public attitudes towards nuclear power (NEA, 2010). As part of this international review, ‘Eurobarometer’ statistics are included which detail public opinion towards nuclear power in member countries of the

European Commission. Relevant Eurobarometer reports have been analysed as part of the NEA's 2010 report. These include: radioactive waste, nuclear safety, energy technologies, climate change and policy issues. A Eurobarometer poll on energy technologies asks if respondents were in favour, or opposed to different sources of energy in their home countries. Figure 6.7 displays public opinion on nuclear power in the UK relative to other European countries with nuclear power programmes. As can be seen, on average, the UK public are slightly more opposed to nuclear power than in favour of it, although the majority of views are balanced (neither in favour of or against nuclear power). The findings of the public consultation on electricity technologies carried out as part of this research (see section 5.1) show similar results, although the leaning is slightly towards favourability (42% favourable towards nuclear power, 40% unfavourable).

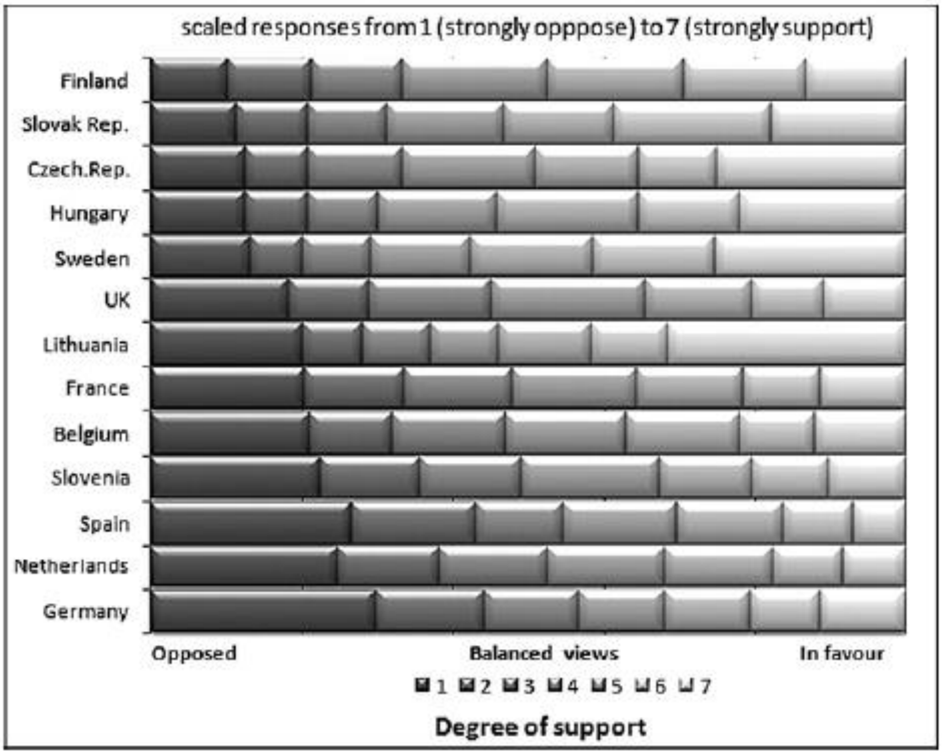


Figure 6.7 Graphical representation of the degree of public support for nuclear power programmes in European countries with nuclear power (1 and 2 responses are opposed, 3, 4 and 5 responses are balanced and 6 and 7 are in favour) (NEA, 2010).

- *Component 2: Growing pressure from public/stakeholders (energy affects economy and environment [public health, pollution, safety])*

Research into opinion trends from stakeholders and the public with regard to energy, the economy and environment has been carried out as part of this research and was detailed in

Chapter 4. Results from the first stage of this research showed that the experts consulted believed global warming to by the most important issue to consider when developing UK energy policy, followed by radioactive waste management, and then large accident fatalities.

6.3.5.3 Subtheme: political support/patronage

<u>Soc 7: Government political support - Government's expressed intention to develop nuclear energy</u>

- *Component 1: Energy plan includes government actions to develop nuclear power (budget and personnel committed)*

With a change in the UK government in May 2010, an updated statement on the policy on energy provision in the UK was provided in the latter half of 2010. The Coalition Government has stated its intention to let the building of new nuclear power stations go ahead as planned under the previous Labour government (WNN, 2010).

- *Component 2: Government's position towards nuclear power (subjective rating)*

Although the new UK Conservative-Liberal coalition government has expressed its support towards a new nuclear power programme (WNN, 2010), it has stated that public funding will not be used to support decommissioning of nuclear plants or waste disposal (WNN, 2010; BBC, 2010).

6.3.5.4 Subtheme: international cooperation

<u>Soc 8: International agreements and conventions</u>

This indicator aims to measure the degree to which a nation is likely to cooperate with international agreements and protocols with regard their own nuclear power programmes. It is composed of four measures, detailed below:

-Party to the NPT and comprehensive safeguards agreement
-Intergovernmental agreements and protocols (including maritime airspace etc.)
-Conventions on nuclear safety
-Convention of physical protection of nuclear material (CPPNM)

- *Component 1: Years in which country became party to the NPT and in which it concluded a comprehensive safeguards agreement*

The UK is signed up to the NPT (Non-Proliferation Treaty) and has been so since 1968. The IAEA's comprehensive safeguards agreement came into force in 1978 (IAEA, 1972).

- *Component 2: Years in which country becomes signatories of relevant agreements and protocols*

The UK is signatory to most if not all relevant agreements. Detailed research on the years when the agreements were signed was outside the scope of this work.

Component 3: Checklist on compliance

Although research into the UK's checklist on nuclear compliance was outside the scope of this work, the UK is known to be compliant with the agreements to which it is a signatory.

6.3.5.5 Discussion of social and political indicators

The social and political theme of the INPD provide information of the relative safety of competing energy technologies, social risk from public perception of nuclear energy, the government intention to develop nuclear energy and international compliance of the nation being assessed.

Although there is currently no accessible data regarding civilian safety, information from the PSI clearly displays that accident fatalities from nuclear energy activities are the lowest of the energy technologies assessed. In addition, the normalised value for nuclear accident fatalities in OECD and EU countries is zero (between 1969-2000), where health and safety regulations are usually much more robust than non-OECD countries.

Public acceptance data for the UK shows that the division between those opposed to and those in support of nuclear power is weighted slightly in favour of the opposition to nuclear power, although conversely findings from this research display public opinion weighted slightly in favour of nuclear power. Opposition to nuclear power by the public can often cause delays in the planning process, meaning that projects are often not delivered on-time and are often more costly than originally envisaged. However, the

Eurobarometer public acceptance results show that opposition to nuclear power is more prevalent in France, where a very successful nuclear programme is run.

The UK has a good track record with regard to international cooperation with international agreements on nuclear safety, therefore any expanded or implemented nuclear power programme is unlikely to be opposed by international organisations on the grounds of this. The UK government's intentions to develop its nuclear power programme were detailed in the latter half of 2010. The government expressed its intention to support private investment of nuclear power in the UK. This indicates that private finance will cover the cost of decommissioning and waste disposal, making nuclear power a less attractive investment.

6.4 Summary

Data for calculation of the IAEA's INPD are mostly identifiable or calculable from government/organisation/company information which is freely available (mostly on the internet). However, some of the indicators are much harder to quantify as they have either: not been directly measured in the past, are composed of two or more measures or it is hard to find information regarding the indicators. All of the five themes have been examined in this application of the INPD to the UK, but with some gaps in information.

The INPD allow a national perspective to be taken with regard to trends and policy implementation that might affect the sustainability of nuclear power in the UK. These trends cannot be accounted for in the framework of indicators within the SPRIng the decision-support framework, as they are technology oriented. In addition to establishing the sustainability of an energy technology or energy mix at a given point in the future, the INPD allows examination of trends that might lead to certain situations and allow nuclear power programme expansion or contraction. Therefore, the IAEA's INPD provide a useful tool in addition to the indicators for sustainability assessment of energy technologies in addressing the drivers and barriers for nuclear power in the UK.

The next chapter applies the SPRIng indicators to assess the sustainability of assessment of future electricity technologies, including the AP1000 nuclear reactor, the European

Pressurised Reactor, a fast reactor and coal-fired power with carbon capture and storage. A multi-criteria assessment of the electricity options is also carried out.

7 Sustainability Assessment of Nuclear Power and Comparison with CCS as a Competing Technology

7.1 Introduction

Over the last ten years, energy policy has been a hot political topic both within the UK and internationally. Many governments have been facing an energy system and energy policy ‘overhaul’ as they struggle to balance low carbon energy provision with security of supply and economic affordability (by government, businesses, organisations and consumers). In the UK, nuclear power has more recently been identified as a viable technology that can provide electricity with much lower carbon emissions compared to many other traditional methods of electricity generation, such as coal- and gas-fired power (BERR, 2008; DTI, 2006a). This endorsement has been made both by the previous Labour Government and the current Conservative party-led Coalition Government (BBC, 2010). Despite this, many stakeholders still believe that other energy alternatives may perform better than nuclear power when compared on the basis of their ‘true’ sustainability (or the triple bottom line – economy, environment and society).

Recent shake-ups in the implementation of nuclear power in the UK have been felt as a direct result of the events at the Japanese Fukushima Nuclear Power Plant following the Tohoku earthquake and resultant tsunami that occurred on 11th March 2011. Although UK public opinion on nuclear power is likely not to be adversely affected by the accident (see sections 5.1.2 and 5.2.3), the stakeholders opposed to nuclear power believe that it is inherently unsafe, costly and poses a large problem with regard to nuclear waste disposal, when compared to other electricity-generating options. In addition, the costs for the companies and consortia involved in the current Generic Design Assessment (GDA) process have risen dramatically - a firm decision on nuclear power’s role in the UK electricity-mix is still to be fully determined following the decision of energy utilities E.On and RWE NPower to withdraw from their consortium bid, Horizon. The Horizon project was dropped, with E.On and RWE blaming problems with raising finance and the cost of decommissioning Germany’s nuclear power stations following that government’s decision to close-down their existing nuclear-generating capacity in the aftermath of the Fukushima disaster (BBC, 2012a). Despite this, EDF and Centrica’s consortium bid to develop nuclear power stations on four existing sites still stands, although the Government is aware of their precarious position with regard to the renewal of nuclear power generation in the UK, given that this consortium represents the largest bid for new nuclear power at current time (BBC, 2012b).

It is evident from the Coalition Government's Energy Bill (DECC, 2012a) that a low carbon energy future together with security of supply are still the main decision criteria for choices on the newest generation of electricity-generating technologies. As well as ensuring a low carbon future and ensuring that these power-generation choices remain reliable for generations to come, the Government will try to ensure that decisions made on energy policy do not cause unnecessary controversy amongst stakeholders, including the general public. Renewable methods of electricity-generation have remained unpopular with some sections of society due to their perceived unpredictability (of wind power in particular), lack of capacity and investment needed for renewable projects to compete (in terms of power produced) with traditional methods of generation, such as coal, gas and nuclear. Although there has been research conducted which supports the view that a low carbon economy could be powered by a range of renewable technologies together with energy-efficiency measures and little or no input from fossils and nuclear sources (Bellona, 2008; Ho *et al.*, 2009), many individuals, organisations and the Government believe that in order to keep down energy prices, ensure energy security as well as create a low carbon economy in an uncontroversial manner, generation from coal, gas and nuclear fuels remain an integral part of the UK's electricity mix.

The traditional methods of electricity-generation mentioned above (coal, gas and nuclear power) provide a base-load supply of power to the UK's electricity supply-mix. Benefits of generating power from large, centralised power stations include: having large point sources for industry; contribution to security of supply (continuous base load generation lessens the chance of 'the lights going out') and particularly in the case of coal- and gas-fired power, the option of producing more electricity which can be fed into the grid easily when demand is high. In addition the valuable benefits of coal, gas and nuclear power, there are many controversial draw-backs of each of these methods of power-generation. Geo-political instability of gas supply to the UK (the UK in now a net importer of gas) is one of the most discussed issues surrounding sustainability of gas power in the UK. Russia's actions in 2009 when gas supply to Ukraine was cut off left the UK Government feeling particularly vulnerable to any future diplomatic issues arising with any natural gas suppliers to the UK. In addition to this energy security issue, gas produces relatively high carbon emissions when compared to low carbon technologies such as renewables and nuclear power, meaning that a high proportion of gas-fired power in the electricity mix would make meeting the UK's future carbon targets much harder. Coal, despite its abundance globally and diversity of countries from which it can be supplied, is the largest contributor globally to carbon emissions (in 2009, 43% of CO_2 emissions from fuel combustion were from coal) when compared to other fuel-based electricity-generating technologies (IEA, 2011a).

7.1.1 Generation III+ nuclear power development in the UK

The Office for Nuclear Regulation (on behalf of the HSE) and the Environment Agency are currently undertraining the process of the Generic Design Assessment for new nuclear reactor designs intended to be built in the UK. The HSE and EA began the long process of the GDA in 2006 following the Government's Energy Review (DTI, 2006b), in which the Labour Government first made serious mentions of a new generation of nuclear power for the UK, with their primary motive being to meet carbon emissions reduction targets. Private energy utilities were then invited to submit proposals for designs of the next generation of power plants in the UK, which would then undergo a lengthy and thorough assessment to assess each reactor design's safety, security, environmental impact and waste management implications. Several companies submitted designs, but the only two that remain in the process are AP1000 and EPR.

The GDA was outlined to be a four-step process beginning in August 2007. The first step (which ran from August 2007 to September 2007) involved short initial discussions between the plant designers and the regulators (HSE and EA) to agree on the requirements needed from each plant design and how the GDA process would take place. Step two of the process was carried out from September 2007 to March 2008. This stage focussed on the designs of the proposed nuclear reactors and whether they were fundamentally acceptable for construction in the UK and if the designs had any shortcomings that could make them potentially unacceptable for UK conditions. Three sets of reports were published from this stage: technical assessment reports; assessment summary reports and a public involvement report. The technical assessments and EA assessment identified no major issues with either of the designs that would make them unacceptable for construction in the UK. It was also made clear in the public involvement report at this stage that the consultation process amongst the public and the GDA team would be an on-going process; no firm conclusions on public acceptability or issues were published at this time (HSE, 2008). Step three of the process (June 2008 – November 2009) included a review of the security and safety of the proposed reactor designs; and finally, step four of the process was intended to gather all of the evidence and information reviewed and collected over the previous stages of the GDA in order for the regulatory bodies to publish their final reports assessing the safety cases of each reactor design. The Office for Nuclear Regulation (ONR) and EA completed their assessments of the safety cases for both the AP1000 and EPR in December 2011 together with a list of issues still to be addressed. Many of these issues are still to be addressed before the GDA process is completed and the design of both reactors can be accepted. The latest quarterly report updating the progress of the GDA process communicated the resolution of a structural issue that had arisen surrounding the design of the EPR, although several GDA issues are outlined to be resolved with this reactor. The state of the Westinghouse GDA process for their AP1000 reactor has been put on hold (the company will not resolve any design issues) until they find a UK customer to construct AP1000 reactors in the UK (HSE, 2012).

Although the HSE has now published its interim acceptance reports for the EPR and AP1000 reactors, the process has been significantly delayed by the unprecedented events in Japan in March 2011, when the Fukushima I Nuclear Power Plant suffered a nuclear meltdown on the International Nuclear Event Scale of level seven (major incident) following the Tohoku earthquake and tsunami. The first quarterly report following the disaster (HSE, 2011) focuses on delays in the GDA process following the events in Japan. The report states that following the disaster, the interim acceptance reports for both plant designs would be delayed, but would be published by June 2011. The interim acceptance reports were finally published in December 2011, adding a further six months’ delay to the process. It is likely that further delays were encountered once the full extent and severity of the Fukushima disaster were realised (the disaster was originally graded at a scale four on the International Nuclear Event Scale, but this was eventually upgraded to a scale seven – the most serious accident classification). In the months following the publishing of the interim acceptance reports from the HSE and EA, development of nuclear power in the UK has been further cast into doubt. Although issues with the EPR design are reaching their final resolution, news reports have suggested that Electricite de France (EDF) are casting doubt on their investment of building nuclear reactors on four sites in the UK (Guardian, 2012a & 2012b). The reasons for this doubt are put down to uncertainties in the Electricity Market Reform (EMR). At the moment, because the current Energy Bill (DECC, 2012a) is still in draft status and under consultation there is no guarantee that the EMR measures will promise return on investment for low carbon energy providers. A decision made to go ahead with new-build nuclear in the UK for EDF would mean a risky investment if a stringent framework is not put into place on time (by the end of 2012) for EDF to make its final decision.

Despite the uncertainty in the development of new nuclear power stations in the UK, the GDA process is still very much live for the EPR and plans to build AP1000 reactors are likely to go ahead if Westinghouse can find a UK customer to build its plants.

7.1.2 Generation IV nuclear power development in the UK

In the UK, the only site upon which a Fast Breeder Reactor has been developed is the Dounreay Nuclear Power Development Establishment (DNPDE) on the north coast of Scotland, located within the Scottish Highlands. The DNPDE was established in 1955 and was active for 39 years, until the last reactor (the Prototype Fast Reactor – PFR), was taken offline in 1994. The Dounreay Fast Reactor (DFR) reached criticality on 14th November 1959 and became the first FBR to supply electricity to the UK grid in 1962. The DFR was shut down in 1977, when the Government focussed its nuclear energy policy on thermal reactors (NEI, 2009). The second FBR commissioned at Dounreay was the Prototype Fast Reactor, which achieved critically in 1974 and began supplying electricity to the grid in 1975. The DFR used a sodium-potassium alloy (NaK) coolant and the PFR was sodium-cooled. The PFR was taken offline in 1994. The Dounreay site is still undergoing decommissioning – the site should be decommissioned and fully closed by 2023 (BBC, 2012c).

Internationally, there are very few FBR’s either currently operating or under construction, primarily due to the economics associated with the fuel cycle of uranium compared to the bred plutonium fuel in a fast reactor. Despite this, research and development into FBR’s is being conducted – the IAEA’s INPRO (International Project on Innovative Nuclear

Reactors and Fuel Cycles) project is conducting work in relation to fast reactors and a closed fuel cycle. In addition to this, Japan, Russia, India and China are all currently operating experimental reactors and FBR's are also in the design phase and under construction in India, Russia, Japan, South Korea and France. In addition to IAEA's INPRO research, a joint collaborative project between Japan's Atomic Energy Agency, France's Alternative Energies Commission and the US Department of Energy is expanding current knowledge and development of FBRs and initiating collaboration between private manufacturing companies and research organisations.

International collaboration and research on FBRs and identification of the state of deployment of these types of reactors (through the projected economics of uranium supply and technical development) has led these reactors to be grouped within the set Generation IV nuclear reactors. The GIF (Generation IV International Forum) stated in 2002 that six classes of future nuclear technologies would be explored as potential contributors to the future of nuclear power; intended commercialisation of these plants is for the years between 2015-2030, or beyond (WNA, 2010). These technologies include: gas-cooled fast reactors, lead-cooled fast reactors, molten salt reactors, sodium-cooled fast reactors, supercritical water-cooled reactors and very high temperature gas reactors.

7.1.3 Carbon capture and storage technology development in the UK

Carbon capture and storage (CCS) technologies are being developed in order to mitigate carbon emissions from coal- and gas-fired power stations by between 80-90% (IPCC, 2005). The Coalition Government stated in 2010 that two thirds of newly commissioned coal-fired power stations must be fitted with CCS, although this ambition was later dropped to one third of coal power plants (The Guardian, 2010). Despite this endorsement, development of CCS power stations is still in its infancy; the UK is still to decide on a project to take forward for DECC's CCS commercialisation competition. DECC's competition is being run in order to determine which coal- or gas-fired power station meets the criteria in order to become the UK's first power station with full-chain (carbon capture, transport and storage) capability demonstrated on a commercial scale. The criteria for any project entering the competition include the following: the project must display full CCS chain, or part-chain with the prospect of being full chain in the future; the project must be located within the UK and the storage site offshore; the project must be fully operational between 2016-2020, but ideally sooner; it should have the ability to abate CO_2 at a commercial scale; and that it should be an electricity generator (DECC, 2012b). Despite the fact that CCS technologies are still not in commercial operation anywhere in the world, many nations' governments are still interested in CCS as a means of reducing CO_2 emissions due to the level of confidence that many technical experts exhibit in the technology – the individual processes do operate on large scales independently of the rest of the CCS life cycle. In addition to this, many small-scale or partial-chain demonstration projects are currently running with significant success.

The Department of Energy and Climate Change (DECC) describe the technology as 'essential' in tackling climate change and securing energy supply. DECC launched the UK CCS competition on 3rd April 2012, which is a 'CCS commercialisation programme', designed to make CCS technologies economical in the electricity market (DECC, 2012b) through a variety of economic, research and technical support measures. DECC has also published a UK CCS Roadmap, which outlines the Government's strategy for development of CCS projects in addition to UK CCS opportunities and barriers to development (DECC, 2012c). The Government aims to commercialise CCS by the 2020s by: injecting £1 billion of capital funding to support commercial-scale CCS; investing £125 million in a CCS research and development programme over four years; developing a market for low carbon electricity to make low-carbon technologies competitive and economically viable; addressing key barriers to deployment of CCS; and engaging with international stakeholders and partners to ensure lessons are learnt from other experts in this field (DECC, 2012c).

Public awareness of CCS technologies is still generally low, and if CCS is to be developed at a commercial scale, public acceptance will at least need to be on a 'passive consent' level, which is far from certain given the level of exposure and understanding of the public to CCS (Brunsting, *et al.*, 2011). Despite these setbacks, it is likely that the Government will continue in its ambition to develop CCS in the UK. An economic development region of CCS in Yorkshire and The Humber is currently being developed in the hope that this innovative technology can bring economic prosperity to this former coal mining area, which currently contains a high proportion of the UK's coal-fired power stations. Eventually, the Government plan to retrofit every operational coal-fired power station in the UK, and it is hoped that all newly commissioned power stations will be fitted with CCS capabilities (DECC, 2012c).

CCS capability for gas-fired power stations remains more uncertain at the current time in the UK –although DECC's commercialisation competition does not exclude gas-fired power stations, the focus of CCS development appears to be centred on the development of coal-fired power stations as more GHG emissions can be saved from CCS applied to coal-fired power. In addition to this, the EU's possible rebranding of gas-fired power to a 'low carbon' source of electricity (The Guardian, 2012c) could mean that there will be less incentive to retrofit or build new gas-fired power stations with CCS capability. The EU's carbon price as a tax on emissions of CO_2 from power stations is also currently too low to provide an imperative incentive for gas-fired power operators to develop CCS for their power stations. This is also true for coal-fired power station operators, although not to the same extent due to the higher emissions of CO_2 and therefore higher tax on coal-fired power stations. It is also likely that coal-fired power station operators want to develop CCS for their power stations in anticipation of a higher carbon tax that could potentially make electricity-generation from this fuel uneconomical without CCS, although currently, the use of coal for electricity generation has become more economic due to the recession and a drop in price of carbon permits (The Guardian, 2012d).

It is clear from DECC's CCS Roadmap (DECC, 2012c) that there are many opportunities and drivers for the development of this technology in the UK. Modelling carried out by DECC as part of 'The Carbon Plan' (DECC, 2011) has shown that CCS can decarbonise the UK economy at 'least cost' compared to other options. It can be inferred from DECC's research and publications on opportunities, development of, research into and barriers to CCS deployment that the Government has full confidence in the UK's ability to be a world leader in this technology. It is against this backdrop that this research on the life cycle impacts of post-combustion carbon capture and storage from a coal-fired power station has been carried out. The following sections outline the three main methods of carbon capture, how CO_2 is then transported and its long-term storage in various repositories.

7.1.4 Summary and justification of technology choices

It is clear from the above discussion on the commissioning of CCS and new nuclear power stations that many uncertainties still exist with both of these being Government-favoured base-load technologies. For example, the waste and decommissioning of nuclear power stations still remains to be fully developed technically with the economic, social and environmental impacts being uncertain. CCS has yet to be demonstrated fully in the UK and storage of CO_2 in the North Sea also poses a technical challenge with possible unknown sustainability (economic, social and environmental) impacts. This chapter attempts to quantify these impacts and evaluate the sustainability of future nuclear as well as CCS technologies as follows:

- three future- generation nuclear power reactors: the Westinghouse AP1000, the Areva European Pressurised Reactor and a Fast Breeder Reactor; and
- a post-combustion capture coal-fired power plant with CO_2 transport and storage.

The AP1000 developed by Westinghouse and the European Pressurised Reactor developed by Areva have been chosen for consideration here as they are currently undergoing the GDA process for siting of these power stations in several chosen locations in the UK. Currently, no sustainability assessment of these reactors in a UK context exists, despite the advanced stage of their implementation. A Fast Breeder Rector has been selected for analysis to identify possible sustainability issues and impacts with this technology which many nuclear technical experts believe addresses sustainability issues associated with thermal nuclear reactors, such as fuel use and fuel costs (ANA, 2005). Although the UK's Fast Breeder Reactors (at Dounreay Nuclear Power Development Establishment) have not received much investment since development of the technology in the 1950s and have since been shut-down, it is possible that Fast Breeder Reactors (FBRs) may receive attention from Government and policy makers in the future as uranium reserves become depleted - known reserves are estimated to last for around 100 years (NEA and IAEA, 2009) and alternative nuclear technologies are considered in preparation for Generation IV reactor initiatives.

Although there have been numerous studies on the life cycle impacts of CCS technologies, none are specific to UK conditions. Given the prominence of CCS in the UK it is important that its sustainability impacts be assessed to help inform decision making on the future of this energy option. A pulverised coal-fired power plant with post-combustion carbon capture is chosen for analysis here. This is for several reasons: pulverised coal power plants have the greatest potential for retrofitting of coal-fired power plants built without capture infrastructure; many of the UK's coal-fired power stations use pulverised coal as their primary fuel – in the case of retrofitting, post-combustion capture is the best option (in terms of ease of retrofit and cost); and data for the life cycle modelling of IGCC (integrated gasification combined cycle) and FBC (fluidised bed combustion) coal-fired power stations are not currently available. Post-combustion CCS is also potentially the 'worst case' option for CCS in terms of materials and energy used (and therefore environmental impacts) as pre-combustion capture and oxy-fuel capture systems will be integrated within the power plant and therefore require less infrastructure and building materials.

Other competing technologies are not considered in this work as they have been assessed elsewhere (Stamford and Azapagic, 2012).

The indicators developed within the SPRIng decision-support framework (Stamford and Azapagic, 2011) have been used to assess the sustainability of these options. These results are presented in the next sections. The description of the technologies considered can be found in Appendix 10.

7.2 Sustainability Assessment of Competing Future Electricity-Generating Technologies

The next sections of this chapter present the results of sustainability assessments of four future electricity-generating technologies from 'cradle to grave'. In each section, the techno-economic results are presented first, followed by the environmental indicators, then finally the social indicators. The first section reviews the sustainability of the AP1000 nuclear reactor, followed by an assessment of the European Pressurised Reactor (EPR), then the European Fast Reactor, and finally, coal-fired power with post-combustion CCS.

7.2.1 Technology assumptions

The following technological characteristics for each electricity technology assessed within this chapter are as follows:

- AP1000 nuclear reactor: 60-year operating life, 85% capacity factor,
- 53-GWd/tU burn-up;
- European Pressurised Reactor: 60-year operating life, 85% capacity factor,
- 53-GWd/tU burn-up;
- European Fast Reactor: data for this reactor is taken directly from NEEDS (2008) (EFR 2025 scenario);
- Coal carbon capture and storage: subcritical pulverised coal power plant, 45-year operating life, 62% capacity factor, post-combustion capture.

Where possible, the results refer to the sustainability of the specific electricity technology considered. However, due to restrictions on data availability for some of the technologies, the results for some of the indicators may refer to generic impacts from similar technologies to those considered here. Where this is the case, this will be referenced within the results of the indicators of the following sections. The indicators are displayed, where possible, in units of kWh of electricity generation.

In the case of the sustainability assessment of a Fast Breeder Reactor, the LCA data that have been used are from NEEDS (2008). The techno-economic and social sustainability assessment of the life cycle of a sodium-cooled FBR, specific to the UK (where possible) is also presented. The results of this section will refer to the sustainability of a sodium-cooled FBR, when data for this specific type of Fast Breeder Reactor are available. Due to restrictions on data availability for FBR technologies (as none are currently in operation in the UK), the results for some of the indicators may be approximated from other types of nuclear reactor. Where this is the case, this will be referenced within the results section.

7.2.2 Assessment of the sustainability of the AP1000 nuclear reactor

7.2.2.1 Techno-economic sustainability

The results of the techno-economic sustainability assessment are discussed under the following headings of the techno-economic issues: operability; technological lock-in; immediacy; levelised cost of generation; cost variability; and financial incentives.

7.2.2.1.1 Operability

Operability of a type of power plant or electricity-generating technology determines how well the given technology works generally, and more specifically this issue identifies if a less-well performing technology under any of the operability indicators might adversely affect the ability to meet electricity demand. On a comparative basis, it is obviously better to select technologies which display better operability overall. However, technologies that may perform less well under one or more of the operability indicators may also work well within an electricity mix. For example, having a greater capacity of pumped storage would lessen the need to have a high proportion of load-following technologies. In addition, technologies such as wind power generate electricity for less time over a given period (on average) when compared to more reliable technologies such as coal- and gas-fired power and nuclear power (due to availability and reliability issues). If the installed capacity of wind power can be matched sufficiently with technologies that may be fired-up quickly at times when electricity generation from wind technologies is relatively low (and electricity demand is high), then reliability and availability issues can be accounted for across the whole electricity mix. Operability is defined in this indicator framework by the following four indicators: capacity factor; availability factor; technical dispatchability; economic dispatchability; and lifetime of global fuel reserves at current extraction rates.

The capacity factor for the AP1000 nuclear reactor is estimated at 93% (Westinghouse, 2011). With Sizewell B's (the UK's only PWR) average capacity factor at 86%, this range indicates a slightly higher capacity factor due to the increased reliability of the evolutionary reactor. However, this capacity factor is estimated and not measured as there are no AP1000 reactors currently operating anywhere in the world.

The availability factor of a power plant or power technology is determined by the average time (expressed as a percentage) that the plant or technology is available to produce electricity. The availability factor for the AP1000 reactor is expected to be above 90% (Westinghouse, 2011). As the highest theoretical availability factor of light water reactors is 93% (Stamford and Azapagic, 2011), the specified availability for the AP1000 is high, partly because the planned shut-down time for refuelling of these reactors has been reduced to a period of 21 days every 18 months, compared to around 40 days for older light water reactors.

Technical dispatchability is defined as the operational ability of a technology or power plant to quickly increase or decrease generation, either when demand increases or decreases or the ability for it to be brought on-line or taken off-line. This indicator comprises several measures: ramp-up rate, ramp-down rate, minimum up-time and minimum down-time. Westinghouse (2011) claims that the AP1000 has a ramp-up rate of 5%/minute. However, this is likely to be a maximum value. Therefore, dispatchability values for PWR have been used in this assessment as follows: 0.17%/min (ramp-up), 0.83%/min (ramp-down) and 999 for both minimum up and down time (Stamford and Azapagic, 2012). Although the AP1000 is the same class of nuclear reactor as the reactor from which the data for minimum up and down times are taken (Sizewell B PWR), the actual minimum up and down times of the AP1000 could differ significantly as these measures can be affected by the operator’s decision to shut down the plant for longer, or vice versa.

Economic dispatchability describes whether it is economically feasible to follow electricity demand (load following). This is determined by calculating the ratio of the capital cost of the technology to its total levelised cost. It is usually not feasible for a technology with high capital costs (and relatively low operating costs) to be offline for a significant proportion of time as the operator would wish to generate enough revenue to pay off the high investment. The ratio of capital cost to total levelised cost for the AP1000 has been determined by using the cost data for the AP1000 – see the section on levelised costs below. The economic dispatchability ratio for the AP1000 has been calculated to be between 54.4-71.3%. This is calculated by taking the ratio of the capital cost to the total levelised cost of generation. These figures suggest that AP1000 are slightly more suitable to load follow economically than previous generation nuclear reactors which have economic dispatchability ratio of 54-84% (Stamford and Azapagic, 2012). However, they are still much less suitable to load-follow compared to coal- and gas-fired reactors, which have lower economic dispatchability ratios due to their lower capital costs.

Lifetime of global fuel reserves at current extraction rates identifies the length of time a technology may be feasible for before alternative fuels or reserves would need to be identified. As this is measured at current usage (extraction rates), it does not take into account the lifetime of a given fuel if a technology became more popular globally. However, it does give an indication of the sensitivity of a technology to the fuel it uses. The use mixed oxide (MOX) fuel in the full core loading is a technical possibility with the AP1000 reactor, which would extend the lifetime of full reserves by up to 5 000 years (if 100% recycled fuel was used) (presentation, G. Butler, July 5th, 2010). However, the current generic design assessment has confirmed that MOX fuel will not be used in UK AP1000 reactors, meaning that the next generation of AP1000 reactors to be built in the UK would operate with 100 years of world fuel reserves left at current extraction rates (IAEA, 2012a).

7.2.2.1.2 Technological lock-in

The technological lock-in indicator measures the operational lifetime of the plant and how flexible the plant or technology might be altered in order to account for changing energy needs. The measure of technological lock-in penalises long lifetimes and rewards ability to provide tri-generation, net negative carbon emissions and/or thermo-chemical hydrogen production. The technological lock-in score calculated for the AP1000 is based on its flexibility to changing energy needs in the future, such as the ability to provide heating and cooling in addition to electricity, capability to produce net negative CO_2 emissions, and its ability to produce hydrogen from thermo-chemical processes. The AP1000 is capable of producing only one out of three of the future energy requirements specified: tri-generation. Tri-generation can be provided by nuclear power plants (heating and cooling in addition to electricity), but the temperatures experience in pressurised water reactors are not high enough for H_2 production. In addition, nuclear power does not have the capability of producing net negative carbon emissions across its life cycle. Therefore, on this ordinal scale fast breeders score a maximum of 10 out of 30. The additional measure – lifetime of the power plant is 60 years for the AP1000. The overall technological lock-in score for the AP1000 is then calculated to be 1.7. This score is the lowest out of nuclear, fossil-based and renewable forms of electricity generation.

7.2.2.1.3 Immediacy

Immediacy of power generation from a technology or power plant measures the time taken from start of construction to completion and therefore takes into account delays specific to a technology type. These delays can potentially cause problems if many power plants or electricity-generating installations are due to be commissioned and therefore a significant proportion of the electricity mix needs to be replaced; delays to construction or insufficient planning might lead to ‘energy gap’ issues. The overall time taken from construction to power plant operation for the AP1000 is estimated to be three years (Westinghouse, 2012). Again (as with the estimation of construction time for fast reactors), this assumption is one that is based on no delays from political opposition, referenda and/or safety and environmental regulations, which, in reality often mean that significant delays are incurred in nuclear projects. This is especially the case in nuclear power plant construction as there is a significant public and political opposition to this form of power generation in the UK. Therefore, this estimate is arguably very optimistic.

7.2.2.1.4 Levelised cost of generation

The levelised cost of generation of a technology type takes account of the full life cycle costs of each technology and the average cost consumers would have to pay for electricity from a particular method of generation in order for the operators to break even. The levelised cost of electricity is calculated by taking the ratio of the total cost of generation (i.e. the full life cycle costs) to the total electricity generated over the lifetime of the power plant and also takes into account appropriate discount factors (5 or 10%). Finding data on the costs of fast breeder reactors relevant to AP1000 development in the UK difficult as there are no operating AP1000 reactors in the UK, or the world. The University of Chicago produced in 2004 a report for the U.S. Department of Energy which estimated AP1000 levelised cost to be between 4.3 – 5 U.S. cents per kWh (The University of Chicago, 2004). This equates to a UK 2012 cost of 2.7 – 3.2 pence/kWh. The IEA also provide cost estimates for an AP1000 reactor based in the U.S. (this is the only OECD country in the report that specifies costs for the AP1000) in their 2010 report on the costs of electricity-generating technologies (IEA and NEA, 2010). At a discount rate of 5%, the levelised costs are estimated at around 3.4 pence/kWh. At a 10% discount rate, this rises to 5.3 pence/kWh. These costs are displayed in Figure 7.1. The IEA costs are slightly higher than the costs projected by The University of Chicago in 2004, but it is likely that the IEA costs are a more accurate estimation of the AP1000's life cycle costings as they are more recent.

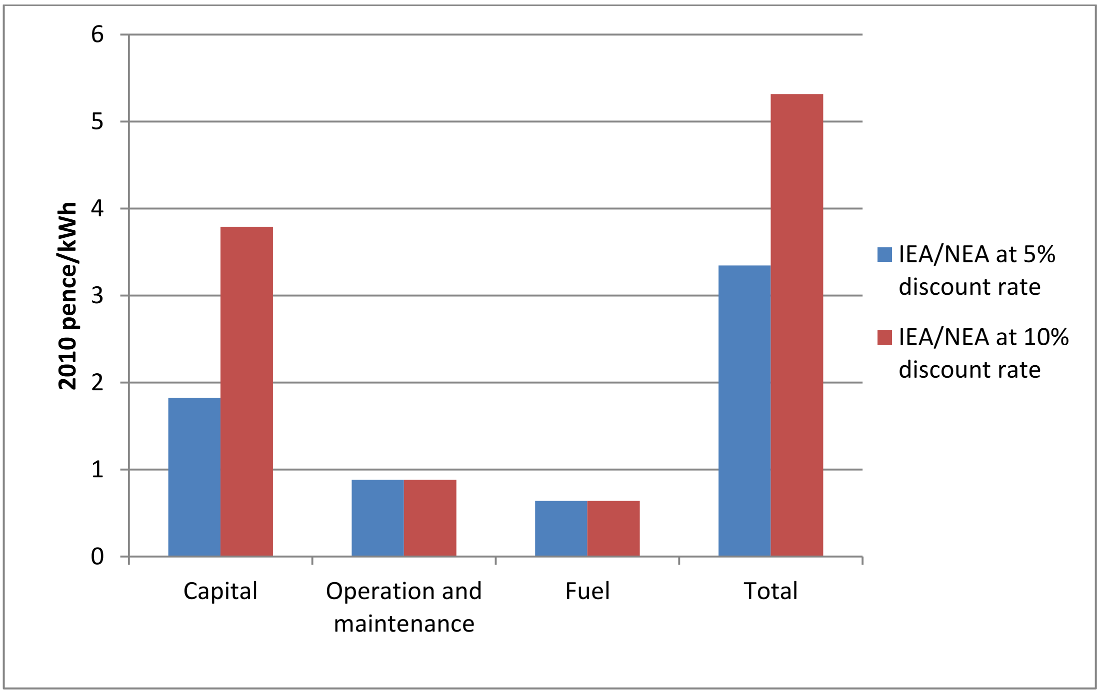


Figure 7.1 Levelised cost estimates for the AP1000 reactor at 5% and 10% discount rates (IEA and NEA, 2010).

7.2.2.1.5 Cost variability

Cost variability of an electricity-generating technology is calculated by taking the ratio of the cost of the fuel to the total levelised cost of electricity and this information allows financial risk from uncertain investment in volatile markets to be taken account of. Using the IEA costs for the AP1000 (at the 10% discount rate), the cost variability ratio for this reactor is 0.12. This low value indicates that fuel costs for the AP1000 have little impact on the total levelised cost and are therefore unlikely to influence electricity prices. The very low contribution of fuel costs to total levelised cost is due to the relatively high capital costs associated with nuclear power plants.

7.2.2.1.6 Financial incentives

The financial incentives indicator for a particular method of electricity generation is a measure of subsidies across the whole life cycle of a technology. This indicator takes into account any subsidies in a UK context that aim to manipulate the free market, including direct payments to the industry, site selection studies and HSE design assessments and hidden subsidies that are not used as market tools (Stamford and Azapagic, 2011).The EU Emissions Trading Scheme would subsidise electricity generation from the AP1000 reactor at a rate of 0.51 p/kWh. This subsidy is specific to all forms of nuclear power generation as none produce direct carbon emissions. Compared to coal CCS, which is also evaluated as part of this work and has a subsidy rate of 0.46 p/kWh, nuclear power receives a subsidy 10.9% higher.

7.2.2.2 Environmental sustainability

The results of the environmental sustainability assessment are discussed under the following headings of the environmental sustainability issues: material recyclability; water eco-toxicity (freshwater eco-toxicity potential [FETP] and marine eco-toxicity potential [METP]); global warming potential (GWP); ozone layer depletion potential (ODP); acidification potential (AP); eutrophication potential (EP); photochemical smog creation potential (POCP); and land use and quality. Prior to this, an overview of the goal and scope of the LCA for the AP1000 reactor and a description of the system to be modelled, assumptions and data will be given.

7.2.2.2.1 Goal and scope of the life cycle assessment

The goal of this LCA is to estimate the life cycle environmental impacts of electricity-generation from the AP1000 nuclear reactor operating in the UK and compare them to other electricity-generating technologies considered in this work (in section 7.2.6). The functional unit is defined as ‘generation of 1 kWh of electricity’. The scope of the study is from ‘cradle to grave’. The following life cycle stages are included within this study: extraction of fuel (uranium) and raw materials, processing and transportation of fuel (uranium); manufacture and construction of power plant and associated infrastructure; operation of power plant to generate electricity; decommissioning of power plant; and waste disposal. The life cycle of the AP1000 is displayed in figure Figure 7.2.

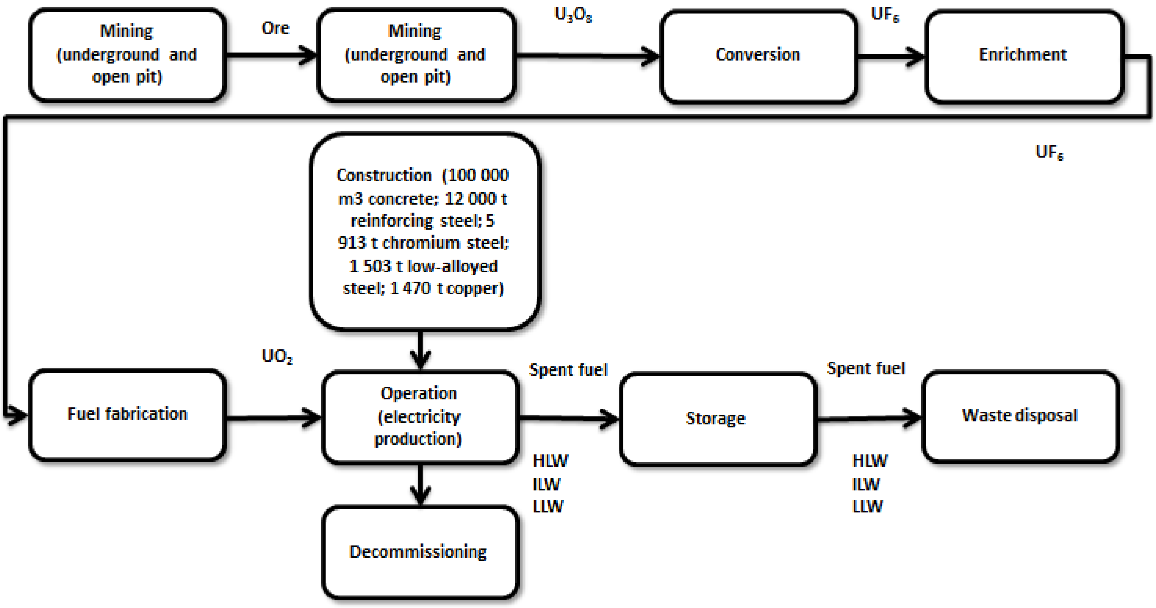


Figure 7.2. Block diagram showing life cycle stages considered in the sustainability assessment of the AP1000 reactor.

7.2.2.2.2 System description, assumptions and data

The LCA of the AP1000 reactor is based on processes within the EcoInvent database that describe a Pressurised Water Reactor with an open fuel cycle. A 1000 MW PWR was modelled with data specific to the UK, where this was possible. There are very few data available that specify the life-cycle inputs for the AP1000 reactor as it is not yet operational anywhere in the world. However, information has been submitted as part of Westinghouse's Generic Design Assessment application to the HSE and EA. Data from these reports have been used to model the AP1000 reactor and relate to construction materials used to build the reactor. In addition to these data, information from British Energy's Environmental Product Declaration (EPD) of Sizewell B has been used for the front-end of the life cycle of the AP1000 reactor. The data used and assumptions made for each nuclear reactor modelled in this chapter are specified in Table 7.1, below.

The front end of the nuclear life cycle for the AP1000 has been modelled using information from British Energy's Environmental Product Declaration of Sizewell B (British Energy, 2008), which is also a PWR, but of the Generation II class. The uranium supply to the UK's thermal nuclear reactors comes from a variety of suppliers and it is currently not possible to specify where the uranium for any AP1000 reactors operating within the UK would come from. Therefore, the best approximation that can be made for uranium supply is to use the information for the only other PWR currently operating in the UK. The impacts for uranium supply would vary by reactor if the UK had nuclear reactors that consumed different types of fuel (for example, mixed oxide fuel or thorium) or if FBRs were in operation. However, this is not the case currently, so it is assumed for the AP1000 that the mining and milling of the uranium is the same as that specified Sizewell B in British Energy's EPD of that reactor. British Energy (BE) specify that uranium is supplied from Australian mines (British Energy, 2008). In reality, uranium supplied to the UK comes from a number of countries including Australia, Kazakhstan and Canada as the largest producers (WNA, 2012c). BE specify that 50% of uranium comes from the Olympic Dam Mine, 25% from the Rossing Mine and 25% from the Ranger Mine Olympic Dam is an underground mine and Rossing and Ranger mines are both open pit mines). However, the only underground and open pit mines available in the EcoInvent database are located in North America, therefore these processes have been used for mining of uranium in the AP1000 model.

BE also specify other processes within the life cycle that are not specific to the Sizewell B fuel cycle. These processes include refinement of the uranium and conversion to uranium hexafluoride. The selected processes within BE's report for these stages are located in Malvesi, France, and Pierrelatte, France, respectively. Uranium fuel for Sizewell B is currently refined and converted in Russia. Despite these differences, the fuel cycle is thought to be representative of a typical PWR operating in the UK within the reference period (British Energy, 2008). The EcoInvent database does not hold data for refinement and conversion specific to the countries specified in the BE study. The only process available within the EcoInvent database is for refinement and conversion located within North America, which has been selected to represent this life cycle stage for the AP1000. The life cycle stages of enrichment and fuel fabrication are specified as processes within Germany in the BE study. Again, these processes do not exist in the EcoInvent database, so the processes which best represent those specified in BE's study have been chosen. For enrichment, the URENCO enrichment plant process has been chosen as this uses centrifugal enrichment of uranium, which is the same process that is specified in BE's life cycle assessment. The fabrication process is selected as a Swiss process, which specifies enriched uranium to 4.2% in fuel elements, which is representative for Sizewell B fuel elements. In addition to these process changes, the electricity used at each life cycle stage or process has been changed to reflect the country specified for each stage in BE's LCA, so that the processes are as representative of BE's specifications as possible.

Specific information about the construction and operation of the AP1000 reactor can be obtained from numerous GDA reports produced by Westinghouse (Westinghouse, 2007a, b, 2009, 2011, 2012) and the HSE's Office for Nuclear Regulation (HSE, 2008, 2009a, b, 2011, 2012). Information from some of these reports has been used in order to model specifications for the AP1000 reactor. These include materials used for construction of the power plant. Data on the operation stage and materials used throughout operation of the power plant are not currently available. Westinghouse state that several material reductions are made in the construction of the AP1000 reactor, in comparison to other PWR designs. Figures are given for amounts of concrete and reinforcing steel used (100 000 m^3 and 12 000 tonnes respectively) (Westinghouse, 2010). Westinghouse also state that the following components of the plant are reduced based on the usual input materials of a typical PWR: 50% fewer safety-related valves; 35% fewer pumps; 80% less safety related piping; 85% less control cable; and 45% less seismic building volume. The concrete and reinforced steel figures provided by Westinghouse relate to the reduction in building volume. It is not clear for these reductions in construction materials what types of metals are used to produce these components of the reactor. A combination of reinforced steel, low-alloy steel, chromium steel, aluminium and copper are used to make various parts of a typical PWR and the reductions in these amounts cannot be determined because the specification for these parts is not included in any of Westinghouse's GDA reports. However, the OECD's report on raw material inputs for future nuclear reactors (OECD, 2011) indicates that the total steel use for the AP1000 is reduced by 73% overall. Therefore, this factor has been applied to the remaining steel inputs (omitting reinforced steel) – low-alloyed steel and chromium steel. This gives in total 32 946 t steel used for the AP1000. The quantities for aluminium and copper remain the same as for a typical PWR, although in reality they are likely to be lower for construction of an AP1000 reactor. The material, fuel and waste data for the AP1000, EPR, Sizewell B and generic UK PWR plant are shown in Table 7.1.

Table 7.1. Table displaying the main construction material inputs and waste outputs for the four nuclear power plants modelled, per power station and per kWh electricity (AP1000, EPR, Sizewell B and generic UK PWR). Resource use/waste production per kWh is displayed in brackets.

Material	AP1000	European Pressurised Reactor	Sizewell B	Generic UK PWR
Reinforcing steel (tonnes)	12 000 (2.13×10^{-8})	46 000 (5.94×10^{-8})	33 700 (9.41×10^{-8})	33 700 (9.41×10^{-8})
Chromium steel 18/8 (tonnes)	5 913 (1.05×10^{-8})	3 750 (4.84×10^{-9})	21 900 (6.11×10^{-8})	21 900 (6.11×10^{-8})
Low-alloyed steel (tonnes)	1 503 (2.66×10^{-9})	1 250 (1.61×10^{-9})	5 570 (1.55×10^{-8})	5 570 (1.55×10^{-8})
Copper (tonnes)	1 470 (2.60×10^{-9})	330 (4.26×10^{-10})	1 470 (4.1×10^{-9})	1 470 (4.1×10^{-9})
Aluminium (tonnes)	200 (3.54×10^{-10})	140 (1.82×10^{-10})	200 (5.58×10^{-10})	200 (5.58×10^{-10})
Concrete (m^3)	100 000 (1.77×10^{-7})	300 000 (3.87×10^{-7})	515 000 (1.44×10^{-6})	169 000 (4.72×10^{-7})
Spent fuel (m^3)	549 (9.73×10^{-10})	914 (1.18×10^{-9})	509 (1.42×10^{-9})	509 (1.42×10^{-9})
Intermediate level waste (m^3)	615 (1.09×10^{-9})	1 730 (2.24×10^{-9})	5 550 (1.55×10^{-8})	5 550 (1.55×10^{-8})
Low level radioactive waste (m^3)	10 600 (1.87×10^{-8})	3 220 (4.16×10^{-9})	17 500 (4.88×10^{-8})	17 500 (4.88×10^{-8})

The next section presents the Life Cycle Impact Analysis (LCIA) of Westinghouse's AP1000 nuclear reactor. Modelling of the Sizewell B reactor, based on British Energy's LCA (2008) and modelling of a generic EcoInvent PWR have also been carried out as part of this work, for comparison purposes. The results are compared to a generic PWR modelled specific to UK conditions and to the life cycle impacts of the modelled Sizewell B nuclear reactor.

7.2.2.2.3 Impact assessment and interpretation of the results

The life-cycle environmental impacts presented below have been calculated using the CML 2001 methodology (CML, 2002), with the exception of the material recyclability indicator and one aspect of the land use and quality issue.

The life cycle environmental impacts of the AP1000 reactor, the UK's Sizewell B reactor (a PWR) and a generic UK PWR have been modelled and are displayed in Figure 7.3. Although the model for the AP1000 has incorporated information on the use of concrete and steel (which are the main construction materials) provided by Westinghouse, information on other material inputs is lacking, meaning that there is some uncertainty in the results for the AP1000. Sizewell B has been modelled using data on materials and inputs from British Energy's environmental product declaration report (British Energy, 2008). Data for the generic PWR has been taken from the EcoInvent database. As shown in the graph, the AP1000 has the lowest environmental impact for every indicator when compared to Sizewell B and the generic UK PWR.

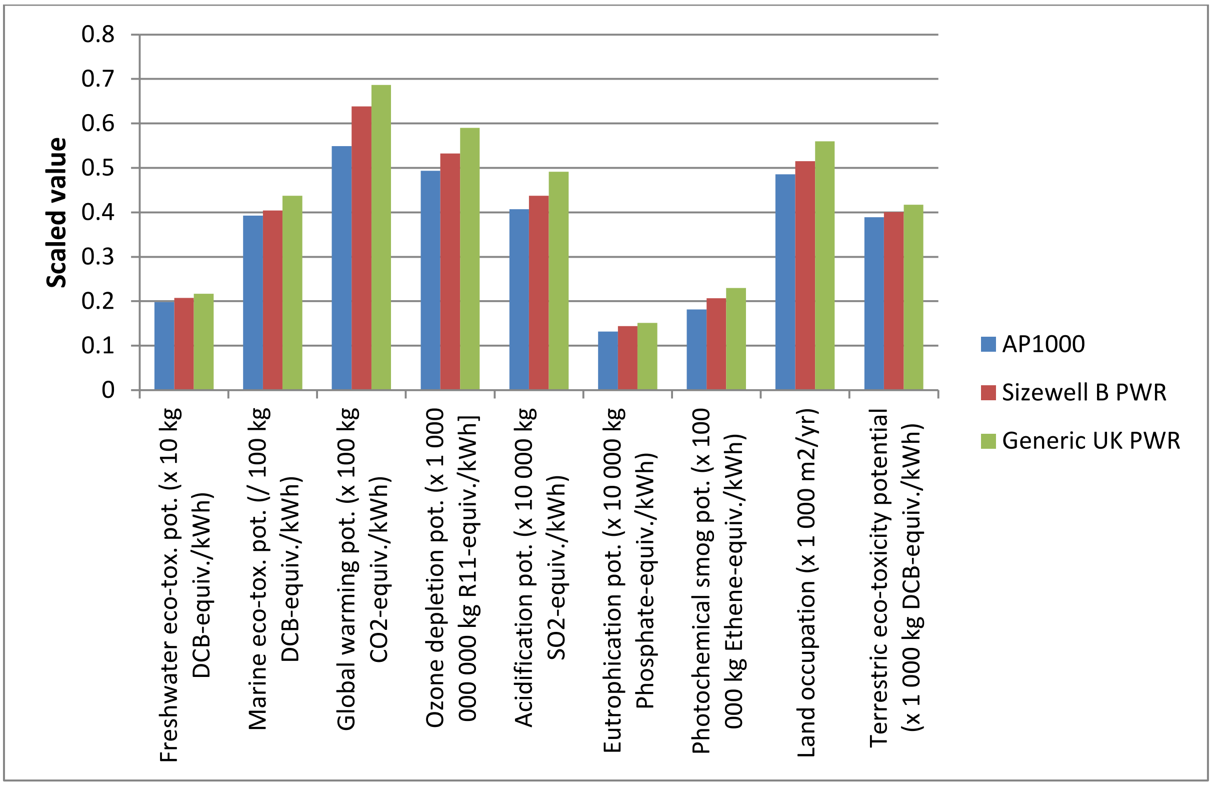


Figure 7.3 Life cycle environmental impacts of the Westinghouse AP1000 nuclear reactor, the UK's Sizewell B Pressurised Water Reactor (based on British Energy, 2008) and an EcoInvent generic Pressurised Water Reactor (EcoInvent, 2010) modelled under UK conditions. [Some indicators have

been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

On average, the AP1000 has impacts that are 7.2% lower than the Sizewell B reactor and 14% lower than a generic EcoInvent PWR modelled under UK conditions. The largest impact decrease from Sizewell B to the AP1000 is for the global warming potential – Sizewell B has a GWP of 6.38 g CO_2-equiv./kWh and the AP1000 has a GWP of 5.49 g CO_2-equiv./kWh (14% less), whilst the largest impact decrease from the UK PWR to the AP1000 is for the photochemical smog creation potential – the generic UK PWR has a POCP of 2.3×10^{-6} kg Ethene-equiv./kWh and the AP1000 has a POCP of 1.81×10^{-6} kg Ethene-equiv./kWh (21% less). Contributions to the environmental impact categories are discussed in turn below to determine the influencing factors for the reduction in environmental impacts compared to the two other PWR options.

7.2.2.2.4 Material recyclability

The material recyclability of the AP1000 is estimated to be around 81.6% (when averaging the recyclable materials used in construction by weight). Nuclear power stations generally use a proportionally high amount of concrete, which usually has a recyclability rate of around 80% (Stamford, 2012). Steel, aluminium and chromium all have recyclability rates of around 100% (Stamford, 2012). Therefore, the total rate of recyclability of components of the AP1000 is close to 80% as 92% of the AP1000 is composed of concrete.

7.2.2.2.5 Water eco-toxicity

The freshwater eco-toxicity (FETP) result for the AP1000 is 2.0×10^{-2} kg DCB-equiv./kWh, compared to Sizewell B's FETP value of 2.1×10^{-2} kg DCB-equiv./kWh. The AP1000 value is 4.5% lower than for Sizewell B and 8.6% lower than for a generic UK PWR (which has an FETP value of 2.2×10^{-2} kg DCB-equiv./kWh. The majority of this impact for the AP1000 comes from the milling life cycle stage (86.9%) and the mining of uranium (6.7%). The life cycle results for FETP can be seen in Figure 7.4. The AP1000 FETP result is lower than the value for Sizewell B as less construction materials are used to build the AP1000 compared to Sizewell B. The difference in impact for the AP1000's FETP compared to a generic UK PWR is also due to more construction materials used in the model of a generic PWR and in addition, the FETP for the enrichment life cycle stage for the generic PWR is much higher that the AP1000 (a 96.7% reduction from the PWR FETP) as the UK PWR model specifies to types of enrichment for the uranium enrichment life cycle stage – 60% of the uranium is enriched at the EURODIF enrichment facility and 40% at the URENCO enrichment facility. Both the AP1000 and Sizewell B models specify that all enrichment takes place at the URENCO enrichment facility. The difference is mostly attributable to the use of diffusion enrichment at the EURODIF facility, whereas the URENCO facility uses centrifugal enrichment.

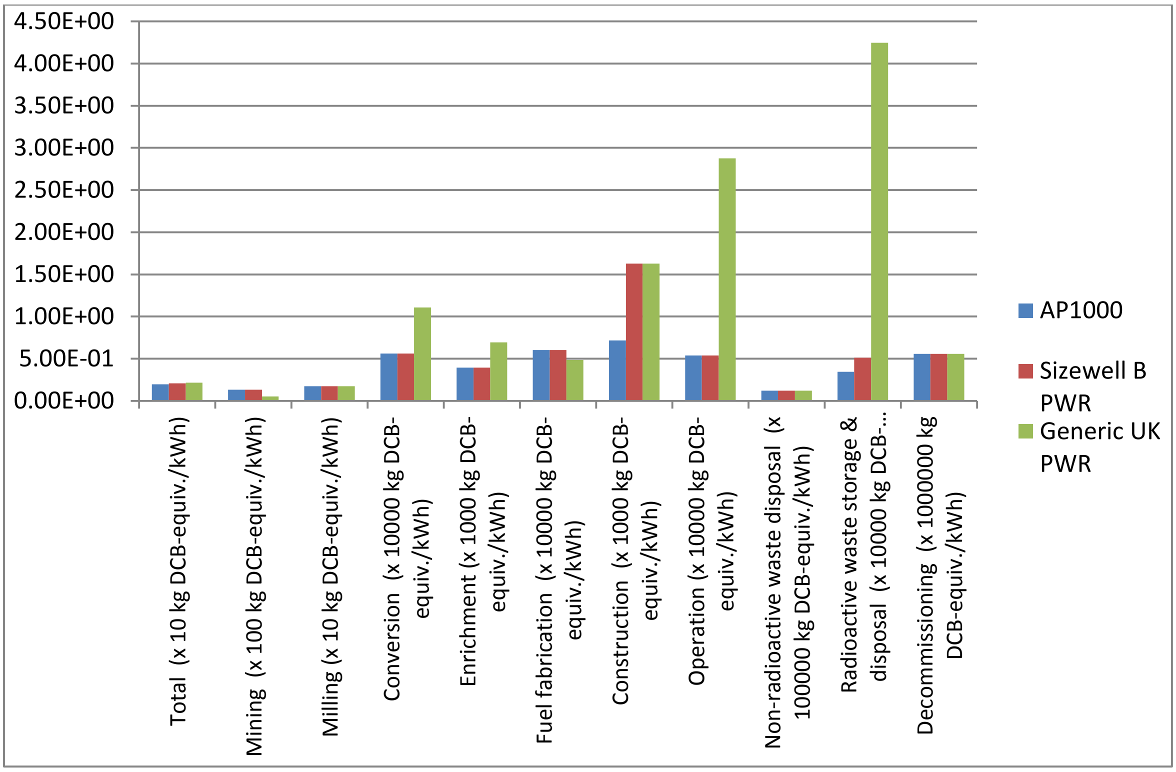


Figure 7.4. Freshwater eco-toxicity potential (FAEP) life cycle impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

The values of the total life cycle AP1000, Sizewell B and UK PWR marine eco-toxicity potential are: 39.2 kg DCB-equiv./kWh, 40.4 kg DCB-equiv./kWh and 43.7 kg DCB-equiv./kWh, respectively. The life cycle impacts of all reactors are displayed in Figure 7.5, below. The majority of the marine eco-toxicity (METP) result for the AP1000 life cycle comes from the milling process (85%), followed by construction of the power plant (5%). The AP1000 METP result is lower than the result for Sizewell B primarily due to lower quantities of materials used in the construction of AP1000 reactors. Again, the METP result is lower for the AP1000 compared to a generic UK PWR due to a larger amount of construction materials used in PWRs and also due to the differences in the types of uranium enrichment used.

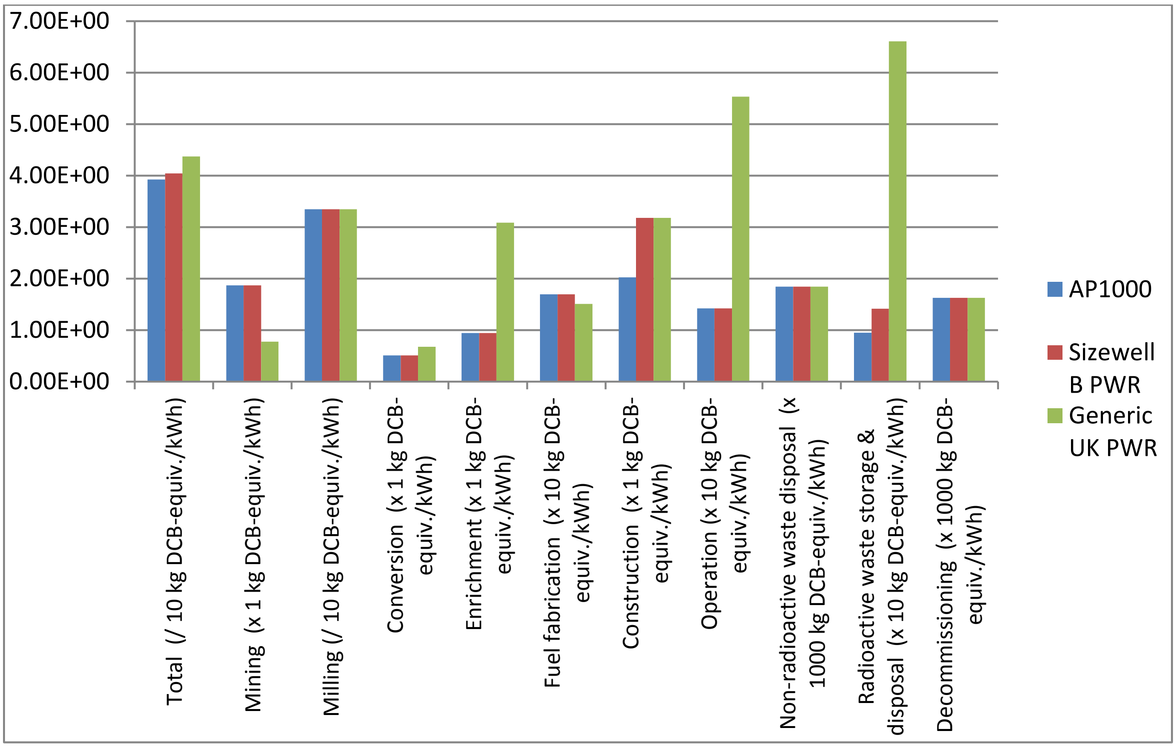


Figure 7.5. Marine eco-toxicity potential (MAEP) life cycle impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.2.2.6 Global warming potential

On average, the AP1000 GWP impacts are 14% lower (5.49 g CO2 eq./kWh) than the model for Sizewell B (6.38 g CO2 eq./kWh); see Figure 7.6. This is due to the lower quantities of materials used in the construction of AP1000. The front end of the life cycle of the AP1000 is assumed to be the same as for Sizewell B, as the same amount of uranium is used per kWh of electricity generated and the uranium is likely to be mined using the same techniques and is likely to undergo the same processing as it does for Sizewell B currently. The AP1000 has a lower GWP impact for radioactive waste storage and disposal when compared to Sizewell B. This is due to the lower estimated levels of spent fuel, intermediate and low level radioactive waste due to best available techniques that will be used in order to minimise waste arising from AP1000 operation that need to be conditioned and stored in final repository.

The GWP for the AP1000 reactor is on average 20% lower than for the generic PWR. This is due to less materials needed in construction and operation and also because only centrifugal enrichment is used in the AP1000 model (60% diffusion enrichment is used in the generic UK PWR model). Despite the overall saving in GWP for the AP1000 model, the AP1000 has higher GWP in the fuel fabrication and mining life cycle stages. The reason for the lower GWP from radioactive waste storage for the AP1000 was described in the above paragraph. The fuel fabrication GWP impact is higher for the AP1000 due to the German electricity mix (British Energy's LCA of Sizewell B specifies the Lingen plant in Germany for uranium fuel fabrication – this assumption is also used for the AP1000) while a generic European mix is specified in the generic UK PWR model (to reflect the variation in source of fabricated fuel for nuclear power plants in the UK). The mining GWP impact is larger for the AP1000 as more uranium is sourced from underground mining than open pit mining (60% for underground and 40% for open pit).

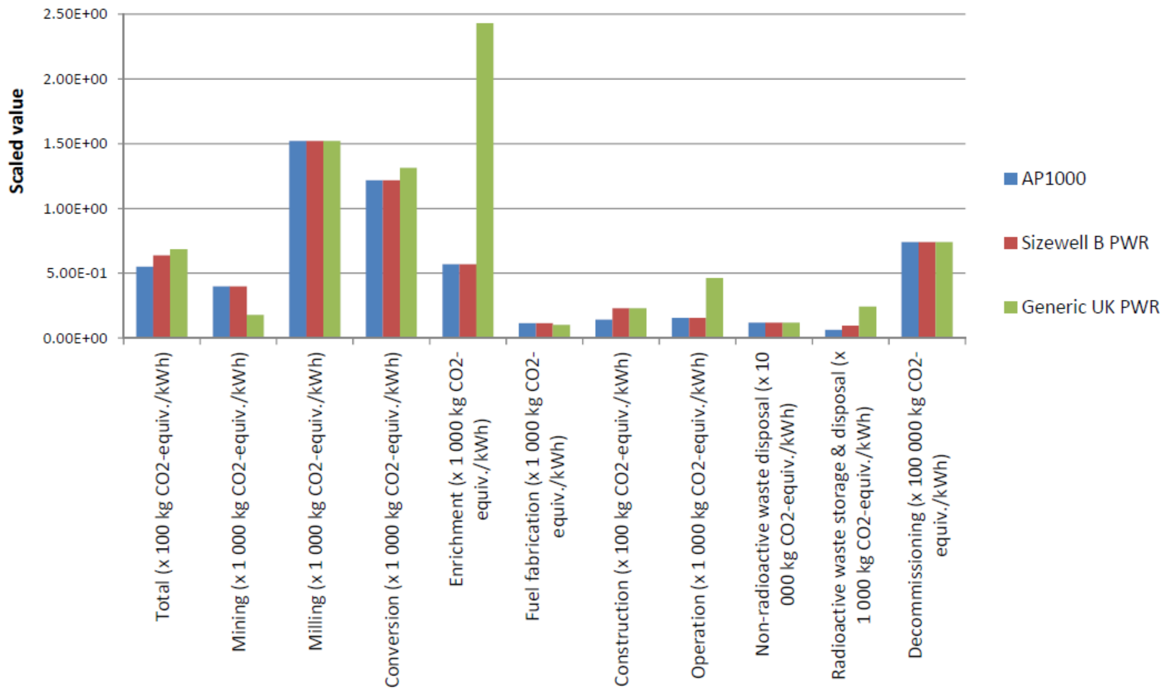


Figure 7.6. Global warming potential (GWP) life cycle impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.2.2.7 Ozone layer depletion potential

The total life cycle ozone layer depletion potential for the AP1000, Sizewell B and UK PWR are as follows: 4.94 x 10^{-10}, 5.32 x 10^{-10} and 5.9 x 10^{-10} kg R11-equiv./kWh. The (ODP) for the AP1000 is 7.2% lower than the impact for Sizewell B and 16.4% lower than the impact for a generic UK PWR. From analysis of the AP1000 life cycle, it can be observed that 32.6% of the ODP comes from the conversion stage and 32.4% from the milling stage (see Figure 7.7). Compared to the ODP in the UK PWR model, savings on ODP are observed in the AP1000's construction, enrichment, operation and radioactive waste storage and disposal life cycle stages. The AP1000 also makes savings in ODP compared to Sizewell B under the construction life cycle stage. Therefore, the primary reason for the lower ODP in the AP100 model when compared to Sizewell B and the UK generic PWR is the amount of materials and energy used in the construction stage of its life cycle.

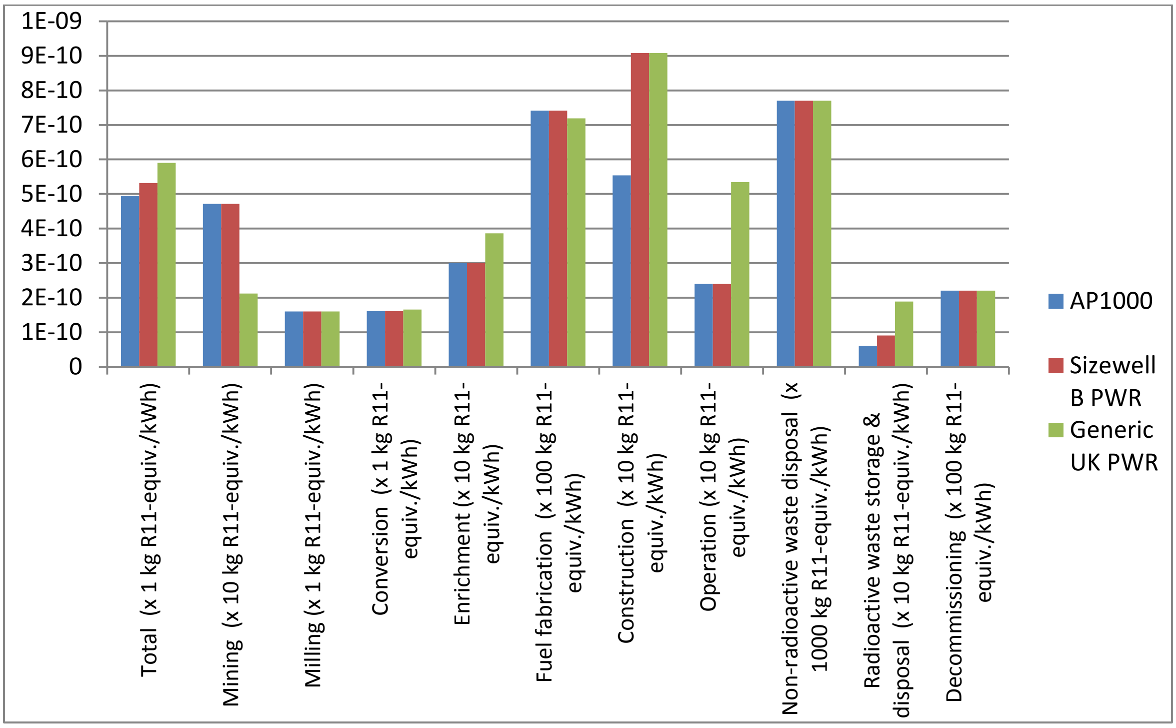


Figure 7.7. Ozone layer depletion potential (ODP) life cycle impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.2.2.8 Acidification potential

The acidification potential (AP) for the AP1000 is 4.07 x 10^{-5} kg SO2-equiv./kWh, which is 7% lower than that for Sizewell B (4.38 x 10^{-5} kg SO2-equiv./kWh) and 17% lower than the AP for the UK PWR (4.91 x 10^{-5} kg SO2-equiv./kWh). The main contribution of the acidification potential for the AP1000 comes from the milling stage of the life cycle (53.3%), see Figure 7.8. In the Sizewell B and UK PWR life cycles, 49.5% and 44.3% comes from milling, respectively. The AP1000 has a lower AP due to less materials being used in construction compared to both Sizewell B and the UK generic PWR and also due to the enrichment methods used in the AP1000 model (which is the same method as used for Sizewell B).

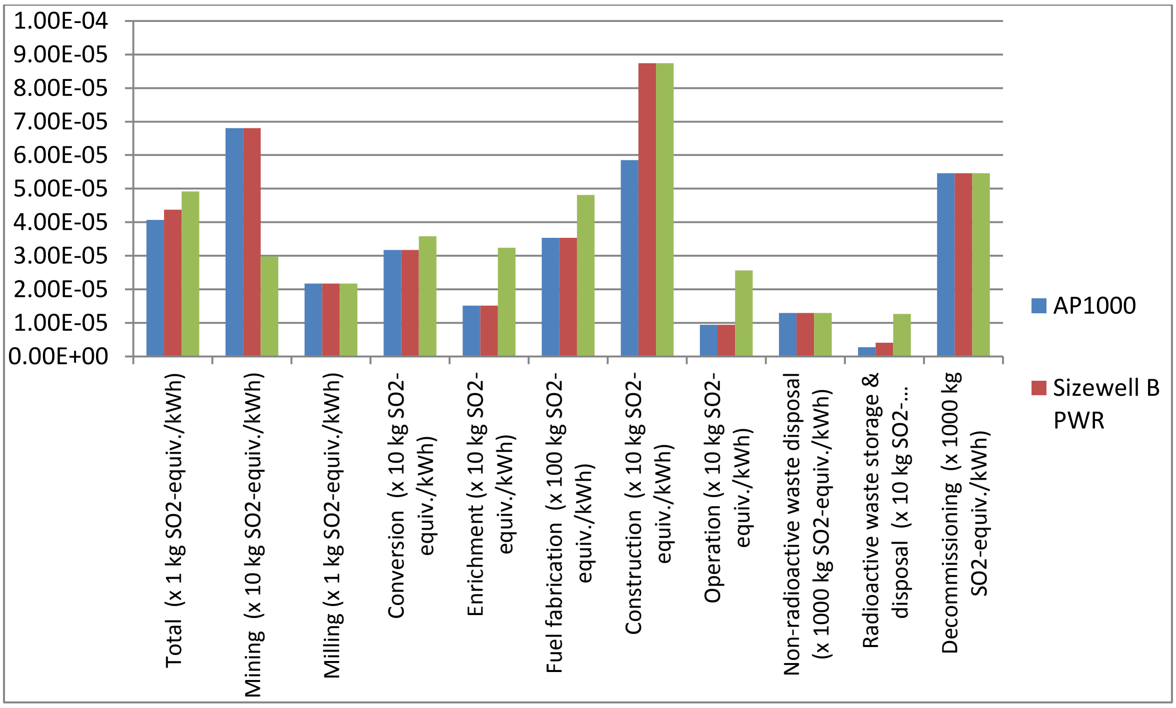


Figure 7.8. Acidification potential (AP) life cycle impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.2.2.9 Eutrophication potential

The total life cycle eutrophication potential impacts for the AP1000, Sizewell B and UK PWR are as follows: 1.32 x 10^{-5}, 1.44 x 10^{-5} and 1.52 x 10^{-5} kg Phosphate-equiv./kWh. The (EP) for the AP1000 life cycle is 8.6% lower than Sizewell B and 13% lower than UK generic PWR life cycles. For the AP1000, the contribution to EP comes mainly from milling of uranium (42.7%) and construction (19%). The Sizewell B model shows that milling is also the highest contributor to EP at 39% of the life cycle impact, and also for the UK generic PWR (37%). The differences in EP between the reactors are due to the construction stage of the AP1000 as fewer materials are used to build the reactor. The total life cycle impacts for EP of all three rectors can be seen in Figure 7.9.

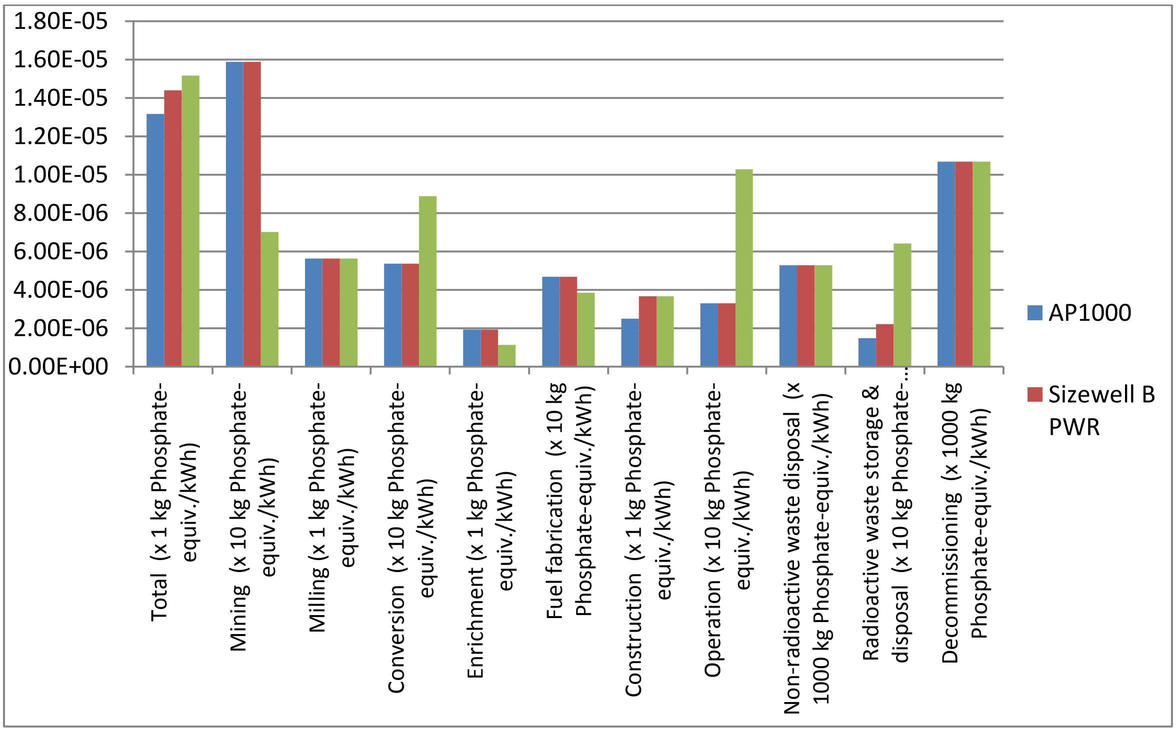


Figure 7.9. Eutrophication potential (EP) life cycle impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.2.2.10 Photochemical smog creation potential

The photochemical smog potential (POCP) result for the AP1000 (1.81 x 10^{-6} kg Ethene-equiv./kWh) is 12.3% lower than the value for Sizewell B (2.07 x 10^{-6} kg Ethene-equiv./kWh) and 21% lower than the value for the UK PWR (2.3 x 10^{-6} kg Ethene-equiv./kWh). The main life cycle contribution to POCP in the AP1000 is the milling stage (50.4%) – see Figure 7.10. For the Sizewell B and AP1000 models, milling is also the largest contribution over both of their life cycles at 44.5% and 39.7%, respectively. Again, the main reason why the POCP vale for the AP1000 is lower than those for Sizewell B and the UK PWR is due to the construction stage of its life cycle.

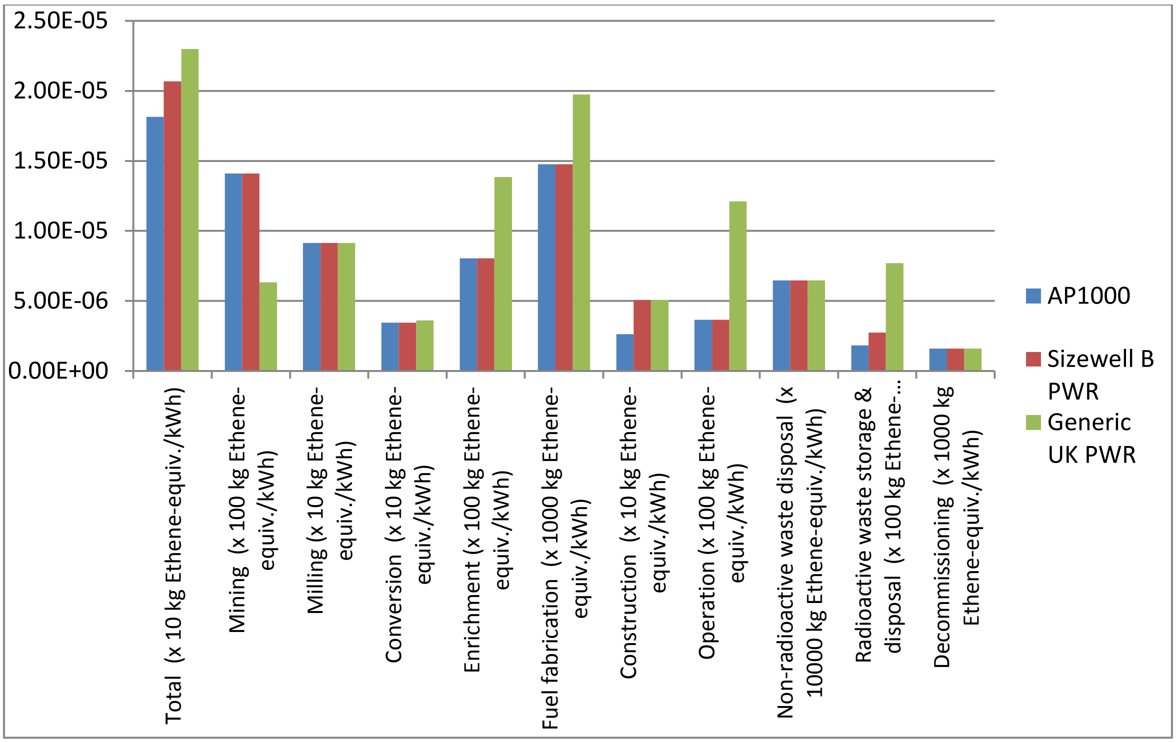


Figure 7.10. Photochemical smog creation potential (POCP) life cycle impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.2.2.11 Land use and quality

Total and life cycle stage land occupation impacts for the AP1000, Sizewell B and UK PWR are displayed in Figure 7.11. Land occupation for the AP1000 is 4.9 x 10^{-4}, 5.15 x 10^{-4} for Sizewell B and 5.6 x 10^{-4} for the UK generic PWR. This is an increase of 4.7% land occupation for Sizewell B from the AP1000 and a 9.4% increase from the AP1000 value compared to the UK PWR. The difference in land occupation for the three reactors is attributed mostly to the construction, conversion and enrichment. For the AP1000, land occupation for construction of the power station contributes 57% to this indicator. The increase in the absolute value for land occupation for Sizewell B and the UK PWR is therefore mostly due to the increased construction needs for those reactors.

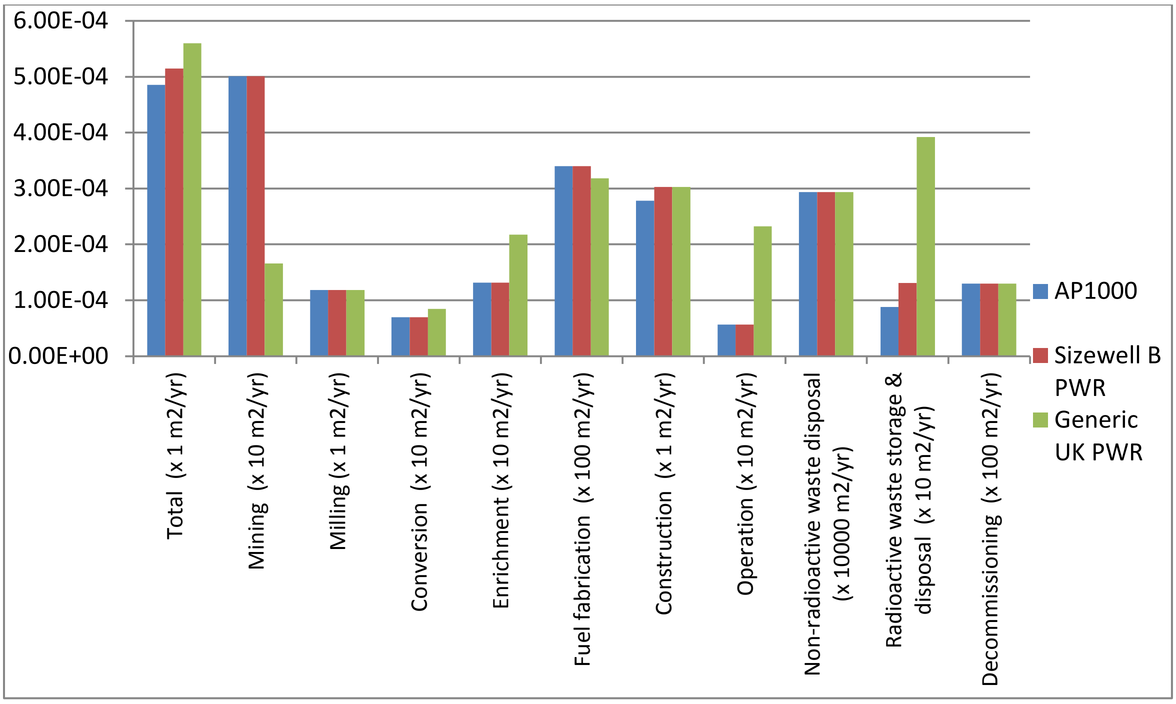


Figure 7.11. Land occupation life cycle impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

At present, there are no plans to build any AP1000 reactors in the UK. Before RWE and E.On pulled out of their bid (named Horizon Nuclear Power) to operate two nuclear reactors in the UK (at the Oldbury and Wylfa sites), the AP1000 was the chosen reactor design to be run as part of the Horizon nuclear venture, along with the EPR. In this case, it is impossible to then determine whether the AP1000 would be built on greenfield or brownfield land. It should be noted that presently, the two sites at the Oldbury and Wylfa power stations are the only two current options to build the AP1000. Therefore, these sites have been considered for the purposes of this indicator. Although the sites have both been previously developed, the new nuclear power plants would be built adjacent to the sites as the older power stations would need to be dismantled and decommissioned over many years. The land that has been planned for new nuclear power development at the Oldbury and Wylfa sites is all classed as greenfield land, indicating that if plans to build AP1000 reactors went ahead, 100% of the land used would be greenfield.

The total life cycle terrestrial eco-toxicity potential (TETP) for the AP1000, Sizewell B and UK PWR can be viewed in Figure 7.12. For the AP1000, Sizewell B and UK PWR these values are: 4.9 x 10^{-4}, 5.15 x 10^{-4} and 5.6 x 10^{-4} m^2/yr, respectively. The land occupation for the AP1000 is 2.9% lower than Sizewell B and 6.7% lower than the value for the UK PWR. TETP for the AP1000 life cycle is attributed mostly to the milling stage (96%). The Sizewell B life cycle model result shows that 93% of its TETP comes from the milling stage and the generic UK PWR shows that 93% of its TETP impact also comes from the milling life cycle stage. An increase in TETP for Sizewell B and the UK PWR comes from the decrease in materials used in construction of the AP1000 reactor. The enrichment stage of the AP1000 and Sizewell B also exhibit lower TETP values than the UK PWR, due to the use of only diffusion enrichment rather than a mixture of diffusion and centrifugal, which is specified in the UK PWR model.

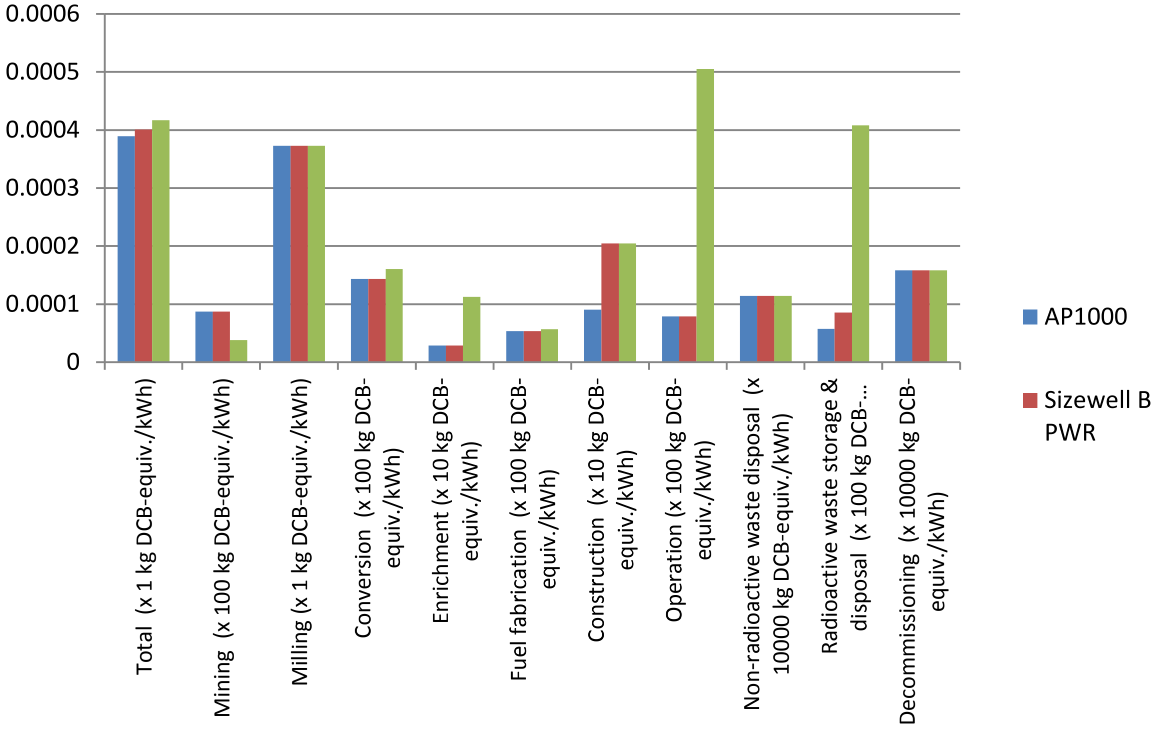


Figure 7.12. Terrestrial eco-toxicity potential (TEP) impact of the AP1000 reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.2.3 Social sustainability

The results of the social sustainability assessment are discussed below under the following headings of the social sustainability issues: provision of employment; human health impacts; large accident risk; local community impacts; human rights and corruption; energy security; nuclear proliferation; and intergenerational equity.

7.2.2.3.1 Provision of employment

Data on the employment for the AP1000 are assumed to be similar to the current PWR design in the UK with direct employment and total employment values of 56 person-years/TWh and 81 person-years/TWh, respectively (Stamford and Azapagic, 2012). Although some aspects of the values used will be overestimations (i.e. the AP1000 is more technically advanced and efficient and therefore likely to employ fewer people), the value used is likely to be a good approximation of employment in the AP1000's life cycle.

7.2.2.3.2 Human health impacts

Human health impacts from toxic substances

Figure 7.13 shows the human toxicity potential of the three nuclear reactors, broken down by life cycle stage. As can be seen, the AP1000 has a HTP of 0.107 kg DCB-eq./kWh or 3.6% lower than the HTP for Sizewell B (0.112 kg DCB-eq./kWh) and 8.5% lower than the generic UK PWR (0.118 kg DCB-eq./kWh).

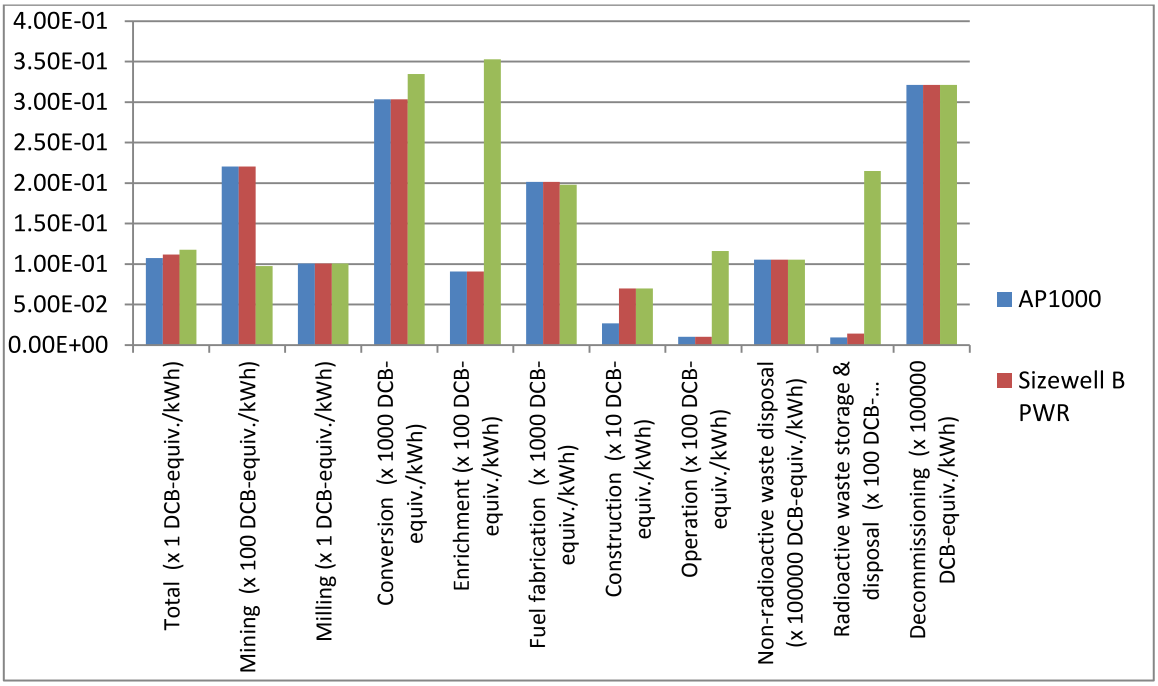


Figure 7.13. Human toxicity potential (HTP) life cycle impact of the AP1000 reactor, Sizewell B and a generic UK PWR broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Human health impacts from radiation

Figure 7.14 displays the health impacts from radiation for the three nuclear reactors. They are: 2.02 x 10^{-8} DALY/kWh for the AP1000 and for Sizewell B and 2.43 x 10^{-8} DALY/kWh for the generic UK PWR. This means that this impact is 17.1% lower for the AP1000 reactor and Sizewell B than that for generic UK PWR. The reason for this difference between the UK PWR and the AP1000 and Sizewell B (which have the same impact) is mainly due to the type of enrichment specified within the generic UK PWR. The enrichment used within this model uses a French electricity mix as the type of enrichment specified for this reactor is the Eurodif enrichment facility in France. The French electricity mix contains a high proportion of nuclear power - over 75% of the country's total electricity supply comes from nuclear reactors (WNA, 2012e). In addition, the generic PWR has higher levels of radioactive waste arisings (see table Table 7.1) than Sizewell B and the AP1000, meaning that the operational stage of the life cycle also displays significantly higher human health impacts from radiation than Sizewell B and the AP1000.

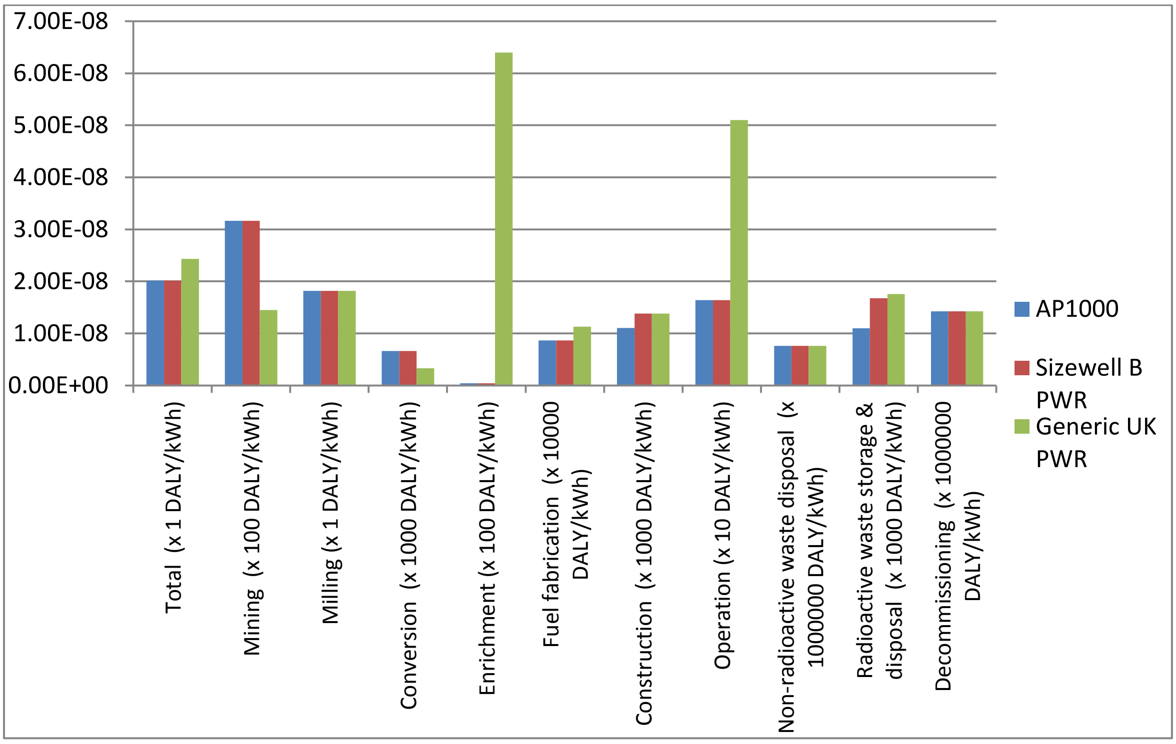


Figure 7.14. Human health impacts from radiation life cycle impact of the AP1000 reactor, Sizewell B and a generic UK PWR broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.2.3.3 Large accident risk

The estimate of potential fatalities from operation of the AP1000 reactor have been calculated using the Probabilistic Safety Assessment of the AP1000 (Westinghouse, 2009), which describes the overall risk of containment failure resulting in accidents when in power and when shutdown. The total power output of the AP1000 reactor over its lifetime (4 997 TWh) and its total operating life (60 Years) are also used to calculate the number of estimated fatalities for this reactor. The total number of deaths that would occur due to a large accident are then calculated by using historical data from the Chernobyl disaster, which has been the largest nuclear accident in history in terms of the number of fatalities resulting from this accident. Several estimates are available for the total number of deaths that occurred as a result of the disaster, but it is widely accepted that between 31-46 deaths happened in the immediate aftermath of the accident (IAEA, 2006). Due the large variation in deaths attributed to the Chernobyl disaster, an upper and lower estimate of large accident fatalities have been calculated for the AP1000 reactor in the range of 1.15×10^{-12} and 5.77×10^{-12} fatalities/kWh.

7.2.2.3.4 Local community impacts

The local community impacts are not calculated for the technologies assessed in this chapter, due to lack of data for these indicators.

7.2.2.3.5 Human rights and corruption

Countries involved in the life cycle stages of nuclear power that is generated in the UK currently include: Namibia (uranium mining), Australia (uranium mining), France (uranium refinement and conversion), Germany (enrichment and fuel fabrication) and the UK (operation and waste disposal). Although the sourcing and production of fuel and materials may vary depending on the power plant operating country, this is, at the current time impossible to determine. Therefore, current uranium sourcing and fuel production life cycle stages taken from a life cycle assessment of the Sizewell B power station are used

(BE, 2008). This gives an average Corruptions Perceptions Index of 7.2 (Transparency International, 2011).

7.2.2.3.6 Energy security

Amount of fossil fuel potentially avoided

This indicator is a calculation of the amount of fossil fuel that would have to be combusted in order to provide an equivalent amount of electricity from a non-fossil fuel source (in this case, the AP1000 reactor). Stamford and Azapagic (2011) determined that 1 kWh of electricity from the UK's current fossil fuel fleet would require 0.2 kg of oil equivalent.

Diversity of fuel supply (DFS)

The overall DFS for the uranium fuel in the UK is estimated at 0.86 (Stamford and Azapagic, 2012), with a score of 1 representing a diverse fully supply and a score of 0 representing a fuel supply that is overly reliant on one nation for its supplies.

Fuel storage capability

This indicator is expressed in terms of energy content of the fuel per unit mass of fuel stored. This indicates fuel storage needs for different types of fuels. The energy density of uranium fuel for thermal reactors has been calculated at 10 million GJ/m^3, assuming a burn-up of 50 GW d/tU (Stamford and Azapagic, 2011).

7.2.2.3.7 Nuclear proliferation

The measure of nuclear proliferation of nuclear technologies is measured using three components to this indicator: use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; and requirement for enriched uranium. The first criterion addresses the ease at which weapons usable spent fuel may be extracted from nuclear reactors. Pressurised water reactors (like the AP1000) are not able to refuel online due to the necessary shut down of the reactor and extraction of the water from the pressure vessel. Enriched uranium is needed to produce fuel for the PWR fuel cycle. Reprocessed fuel can be used in the AP1000, but the current UK energy policy is not to use processed fuel in its thermal reactors. Therefore, the AP1000 reactor scores one out of a maximum three for nuclear proliferation potential using the above measures.

7.2.2.3.8 Intergenerational equity

Intergenerational equity is defined as problems created for future generations to manage. Depletion of resources and long-lived hazardous waste are obvious issues associated with future generations. Climate change is another issue that will affect people many generations into the future, however, this issue is addressed under the global warming potential indicator under the environmental set of measures. Here, intergenerational equity is defined through the use of several measures: use of abiotic elemental resources; use of abiotic fossil resources; volume of radioactive waste to be stored; and volume of liquid CO_2 to be stored.

Use of abiotic elemental resources

Over the whole life cycle, the AP1000 reactor's elemental abiotic resource depletion rate is 3.94×10^{-5} kg Sb-equivalent, which is 11.3% less than the impact for Sizewell B power station (with an impact of 4.44×10^{-5} kg Sb-equivalent per kWh) and 17.2% less than the generic UK PWR (with an impact of 4.76×10^{-5} kg Sb-equivalent per kWh). Figure 7.15 displays the life cycle impacts of the three nuclear reactors, broken down by life cycle stage.

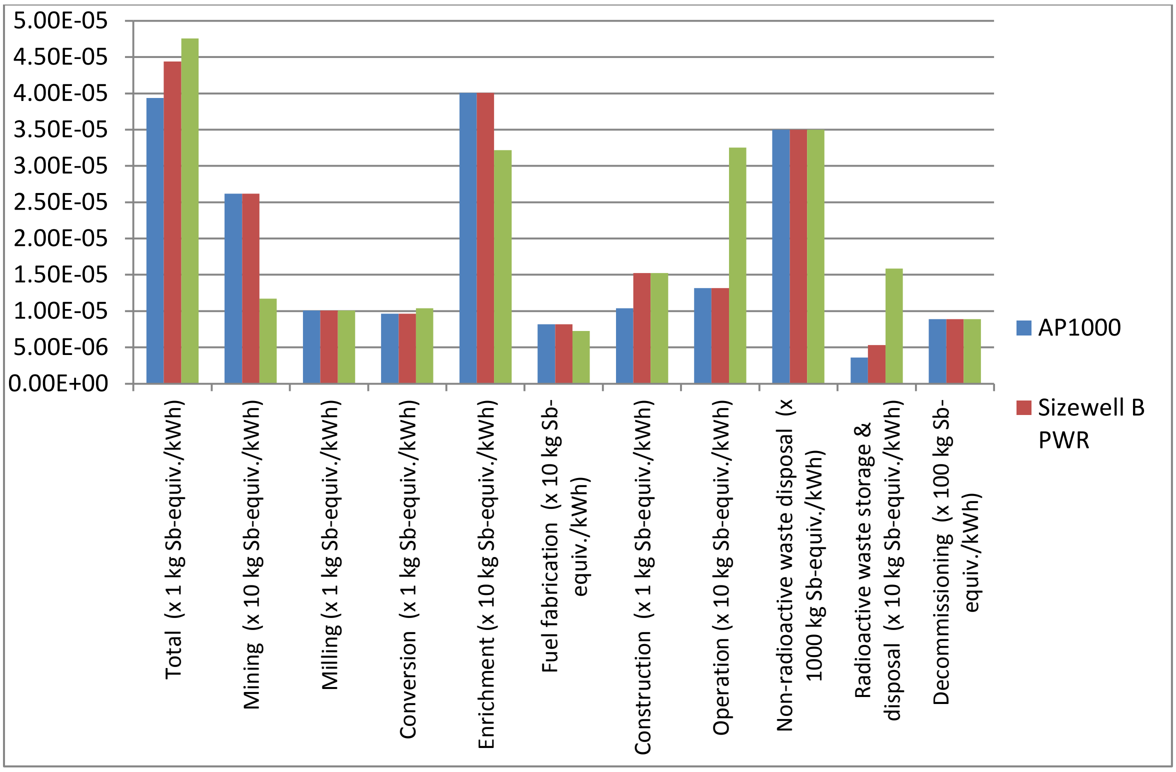


Figure 7.15. Use of abiotic elemental resources life cycle impact of the AP1000 reactor, Sizewell B and a generic UK PWR broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Use of abiotic fossil fuel resources

Over the whole life cycle, per kWh the AP1000 depletes abiotic fossil resources at a rate of 0.076 MJ, Sizewell B has an impact of 0.084 MJ per kWh and the generic UK PWR has an impact of 0.091 MJ per kWh. The AP1000 reactor uses abiotic fossil resources 10% less than the impact for Sizewell B power station and 16.7% less than the generic UK PWR. Figure 7.16 displays the life cycle impacts of the three nuclear reactors, broken down by life cycle stage.

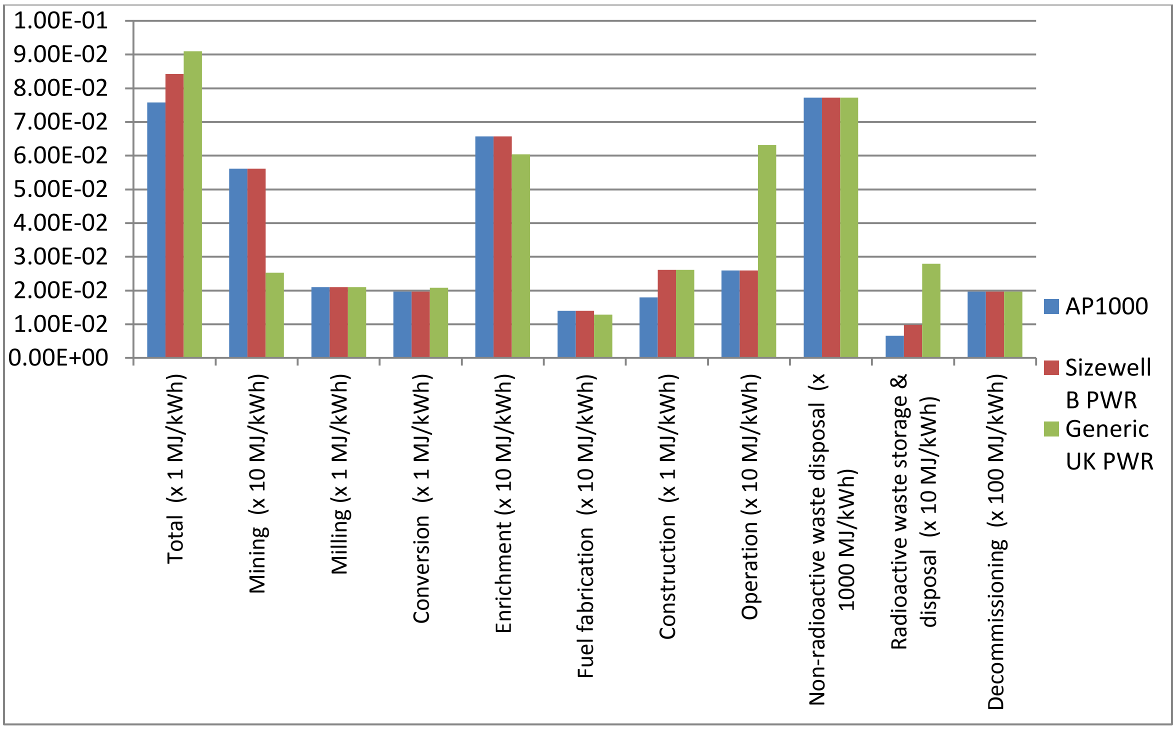


Figure 7.16. Use of fossil fuel resources life cycle impact of the AP1000 reactor, Sizewell B and a generic UK PWR broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Radioactive waste to be stored

The radioactive waste to be stored value is taken from Stamford (2012). A value of 1.2 m^3/TWh is assumed (Stamford, 2012).

7.2.3 Assessment of the sustainability of the European Pressurised Reactor

7.2.3.1 Techno-economic sustainability

The results of the techno-economic sustainability assessment are discussed under the following headings of the techno-economic issues: operability; technological lock-in; immediacy; levelised cost of generation; cost variability; and financial incentives.

7.2.3.1.1 Operability

The capacity factor for the EPR nuclear reactor has been estimated to be 91% (WNA, 2012d). With Sizewell B's (the UK's only PWR) average capacity factor at 86%, this range indicates a slightly higher capacity factor due to the increased reliability of the evolutionary reactor. However, the capacity factor for the UK EPR is predicted and not measured, as the EPR design specification for the UK is not currently in operation.

The availability factor for the EPR reactor is expected to be 92% (WNA, 2012a). As the highest theoretical availability factor of light water reactors is 93% (Stamford and Azapagic, 2011), the specified availability for the EPR is high, but Areva state that the high availability factor is achievable through several measures: more efficient maintenance; access to the reactor building during operation to allow preparation of maintenance and refuelling tasks to be carried out ensuring minimum loss of availability; and shorter outages through simplification of equipment and standardisation (Areva NP and EDF, 2012).

Technical dispatchability comprises: ramp-up rate, ramp-down rate, minimum up time and minimum down-time. The values for dispatchability from Stamford (2012) are used in this assessment and comprise: 0.17%/min (ramp-up), 0.83%/min (ramp-down) and 99 for both minimum up and down time.

The economic dispatchability ratio for the EPR has been calculated to be between 64.4-79.2% (with the former figure being determined using a 5% discount rate and that latter with a 10% discount rate of the levelised cost data, below). These figures suggest that the EPR is slightly more suitable to load follow economically at a 5% discount rate. Again, as with the AP1000, this reactor is much less suitable to load-follow compared to coal- and gas-fired reactors, which have economic dispatchability rates of around 20% (Stamford and Azapagic, 2011).

The current lifetime of uranium reserves at current extraction rates is approximately 100 years (IAEA, 2012a). The use mixed oxide (MOX) fuel in the full core loading is a technical possibility with the EPR reactor, which would extend the lifetime of full reserves by up to 5 000 years (if 100% recycled fuel was used). However, the current generic design assessment has confirmed that MOX fuel will not be used in UK EPR reactors. The EPR reactor makes savings on uranium use as the reactor uses 17% less uranium per unit of power produced. This means that EPR reactors to be built in the UK would operate with 120 years of fuel reserves left at current extraction rates.

7.2.3.1.2 Technological lock-in

The technological lock-in score calculated for the EPR is based on its flexibility to changing needs in the future, such as the ability to provide heating and cooling in addition to electricity, capability to produce net negative CO_2 emissions, and its ability to produce hydrogen from thermochemical processes. The EPR is capable of producing tri-generation only out of the three measures (this is the same results as for the AP1000, which is also a PWR). On this ordinal scale, therefore, the EPR scores of 10 out of 30. The lifetime of the plant is also 60 years for the EPR (Westinghouse, 2009). The overall technological lock-in score for the EPR is then calculated to be 1.7. This score is the joint-lowest (with the AP1000) out of nuclear, fossil-based and renewable forms of electricity generation.

7.2.3.1.3 Immediacy

The overall time taken from construction to power plant operation for the EPR is estimated to be around 42 months, or three and a half years (BBC, 2008; Areva, 2005). In the case of France's first EPR (Flamanville 3), the construction time was estimated to last for 54 months (four and a half years) in 2007 (NCE, 2009). Again, these assumptions are based on no delays from political opposition, referenda and/or safety and environmental regulations. It should be noted that the construction time of individual reactors will vary depending on the location due to varying site conditions, industrial organisation and policies and local working conditions (Areva, 2005). Construction of the first built EPRs, the Finish Olkiluoto 3 power plant and the French Flamanville 3 power plant commenced in August 2005 and December 2007, respectively. Olkiluoto 3 is now estimated to be generating electricity in 2014 (Reuters, 2011), and Flamanville 3 should be online by 2016 (NEI, 2011) with total construction times of both reactors of nine years. The specific site problems mentioned above can in part be attributed to the delay of Olkiluoto – significant delays have been endured due to problems with construction of the power plant and expertise in this area in Finland. In addition, deficiencies in the safety-related design and manufacturing were recognised by the Finish Radiation and Nuclear Safety Authority, which added further delays to the construction of Olkiluoto and reinforcement of the reactor building to withstand an aeroplane impact (New Scientist, 2007; WNN, 2007). The Flamanville plant has suffered a series of delays due to quality control problems with the welding quality and cracking of the reactor container (Bloomberg, 2010; NEI, 2011), setting back the original 54 month construction schedule from 2007, to nine years (NEI, 2011).

7.2.3.1.4 Levelised cost of generation

Finding data on the costs of the EPR, relevant to the UK is a hard task currently there are no built and operating EPR reactors in the UK, or the world. The IEA also provide cost estimates for the EPR reactor based on the projected costs of two EPR reactors operating within Europe and OECD countries in their 2010 report on the costs of electricity-generating technologies (IEA and NEA, 2010). One of the reactor cost estimates is based on the French Flamanville power plant. At a discount rate of 5%, the IEA EPR data modified to reflect EPR costs in the UK, on average, 4.0 pence/kWh. At a 10% discount rate, this rises to a cost of 6.9 pence/kWh. These costs are displayed in Figure 7.17, below.

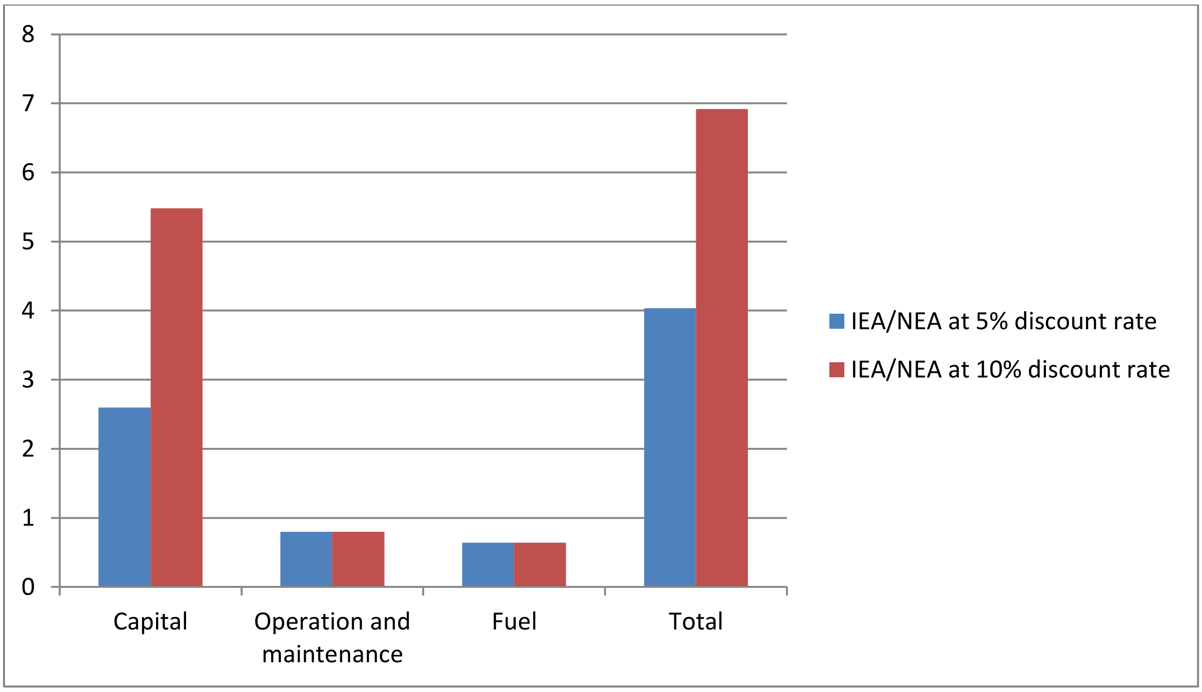


Figure 7.17. Levelised cost estimates for the EPR reactor at 5% and 10% discount rates (IEA and NEA, 2010).

7.2.3.1.5 Cost variability

The cost variability ratio for the EPR is 0.09 (using the IEA costs for the EPR at the 10% discount rate). This is a low ratio and displays that fuel costs for the EPR have little impact on the total levelised cost and are therefore unable to induce large costs fluctuations to electricity customers. The very low contribution of fuel costs to total levelised cost is due to the relatively high capital costs associated with nuclear power plants.

7.2.3.1.6 Financial Incentives

The EU Emissions Trading Scheme would subsidise electricity generation from the EPR and nuclear power generally at a rate of 0.51 p/kWh.

7.2.3.2 Environmental sustainability

The results of the environmental sustainability assessment are discussed under the following headings of the environmental sustainability issues: material recyclability; water eco-toxicity; global warming potential (GWP); ozone layer depletion potential; acidification potential (AP); eutrophication potential (EP); photochemical smog creation potential; and land use and quality. Prior to this, an overview of the goal and scope of the LCA for the European Pressurised Reactor and a description of the system to be modelled, assumptions and data will be given.

7.2.3.2.1 Goal and scope of the life cycle assessment

The goal of this life cycle assessment is to estimate the life cycle environmental impacts of electricity-generation from the European Pressurised Reactor operating in the UK and compare them to other potential future electricity-generating technologies. The functional unit is described as ‘generation of 1kWh of electricity’. The scope of the study is the full life-cycle of the power plant, i.e. from ‘cradle to grave’. The following life cycle stages are included within this study: extraction of fuel (uranium) and raw materials, processing and transportation of fuel (uranium); manufacture and construction of power plant and associated infrastructure; operation of power plant to generate electricity; decommissioning of power plant; and waste disposal. The life cycle of the EPR is displayed in Figure 7.18.

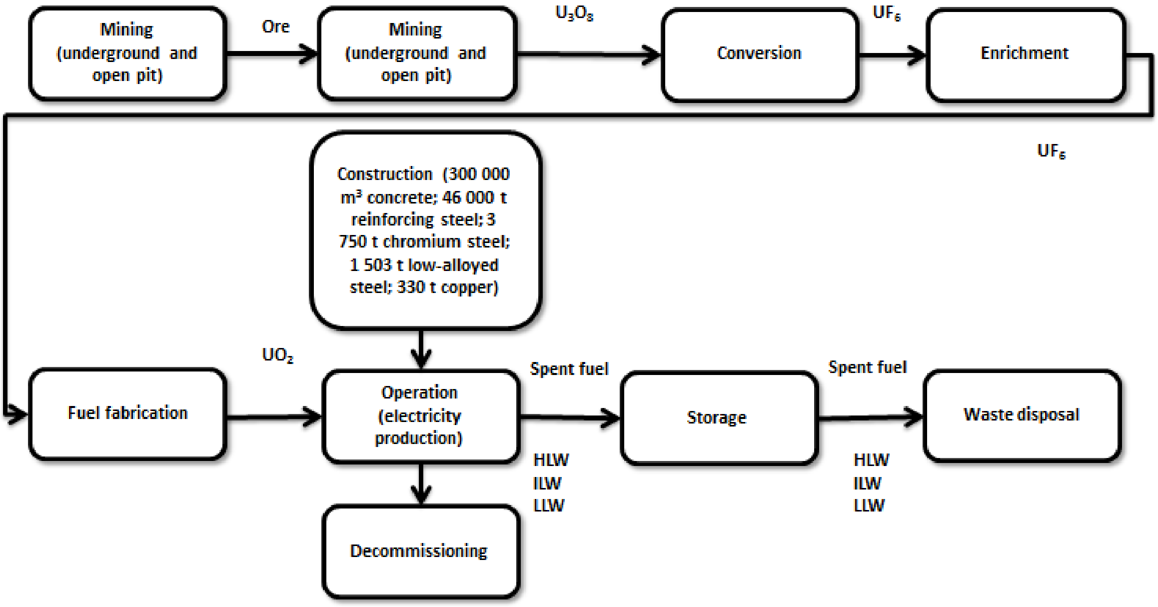


Figure 7.18. Block diagram showing life cycle stages considered in the sustainability assessment of the European Pressurised Reactor.

7.2.3.2.2 System description, assumptions and data

The LCA of the EPR is based on processes within the EcoInvent database. The same general specifications for the EPR have been selected that were selected for the AP1000 (i.e. a 1000 MW power station, specific to the UK). Little information and life cycle inventory data are available for the EPR. Information submitted as part of Areva's application to operate EPR's in the UK is available from the Generic Design Assessment process websites (the Office for Nuclear Regulation, HSE and EA sites). Data from these reports have been used to model the EPR reactor and relate to construction materials used to build the reactor and the amount of uranium used over the operational lifetime. Information from British Energy's Environmental Product Declaration (EPD) of Sizewell B has been used for the front-end of the life cycle of the EPR (including mining to fuel fabrication), this approach was also taken with the modelling of the AP1000 reactor. The only difference in the model for the front end of the fuel cycle is the amount of uranium specified for use in the EPR. Areva state that 17% less uranium is needed in order to generate the same amount of electricity as a typical PWR (Areva, 2006). The amount of uranium specified for the EPR compared to other nuclear reactors modelled within this chapter can be seen in Table 7.1.

Specific information about the construction and operation of the EPR can be obtained from numerous GDA reports produced by Areva (see www.epr-reactor.co.uk) and the HSE's Office for Nuclear Regulation (www.hse.gov.uk/nuclear/). Information from some of these reports has been used in order to model specifications for the EPR. These include materials used for construction of the power plant. Data on the operation stage and materials used throughout operation of the power plant are not currently available. The reduction in material use in construction of the EPR compared to older nuclear power reactors can be referred to in Table 7.1.

The next section presents the Life Cycle Impact Analysis (LCIA) of Areva's European Pressurised Reactor. The results are compared to a generic PWR modelled specific to UK conditions and to the life cycle impacts of the modelled Sizewell B nuclear reactor, for comparison.

7.2.3.2.3 Impact assessment and interpretation of the results

The life-cycle environmental impacts presented below have been calculated using the CML 2001 methodology (CML, 2002), with the exception of the material recyclability indicator and one aspect of the land use and quality issue.

The life cycle environmental impacts of EPR, the UK's Sizewell B reactor and a generic UK PWR are displayed in Figure 7.19. The model has taken into account the likely front end fuel processes and the variance in construction materials used in order to build an EPR reactor. Information on the operational and decommissioning life cycle stages are lacking and therefore generic PWR data have been substituted here. This means that there is some uncertainty in the results of this LCA for the EPR.

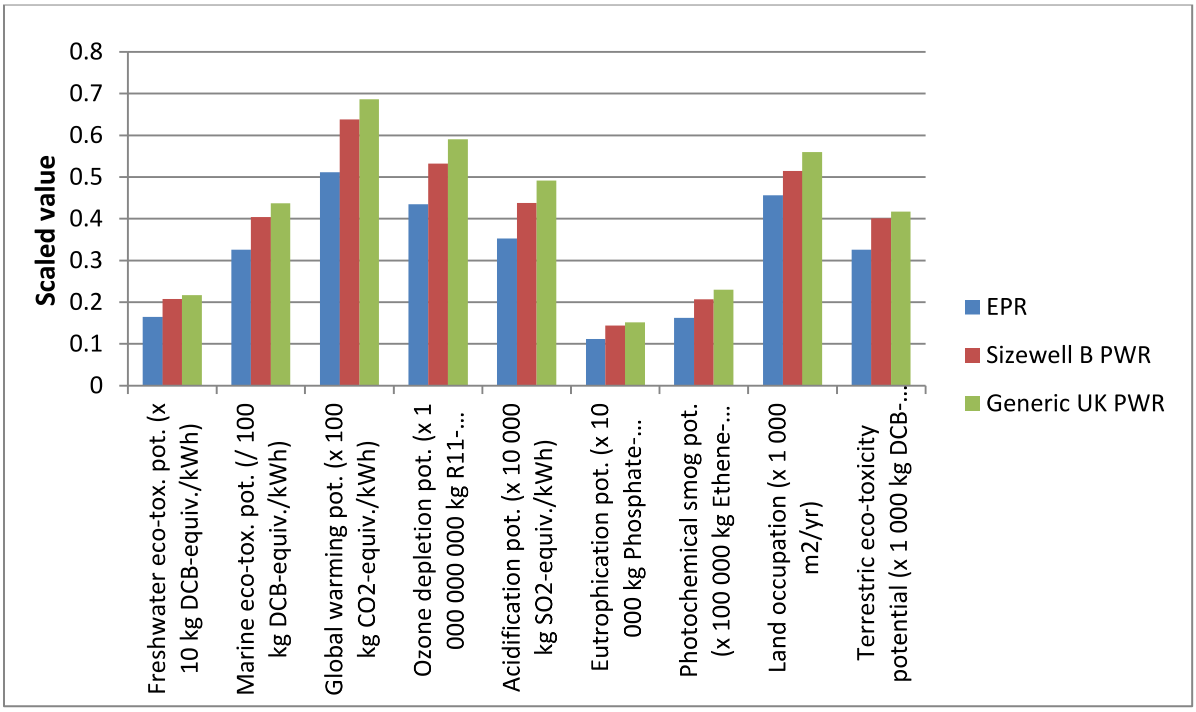


Figure 7.19. Life cycle environmental impacts of the Areva European Pressurised Reactor, the UK's Sizewell B Pressurised Water Reactor and an EcoInvent generic Pressurised Water Reactor modelled under UK conditions. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

As shown in Figure 7.19, the EPR has the lowest environmental impact for every indicator when compared to Sizewell B and the generic UK PWR. On average, the EPR has impacts that are 19% lower than the Sizewell B reactor and 25% lower than a generic EcoInvent PWR modelled under UK conditions. The largest impact decrease from Sizewell B to the EPR is under the eutrophication potential indicator – the value Sizewell B is 1.44 x 10^{-5} kg Phosphate-equiv./kWh and the value for the EPR is 1.12 x 10^{-5} kg Phosphate-equiv./kWh (22% less). The largest impact decrease from the UK PWR to the EPR is under the photochemical smog creation potential indicator (2.3 x10^{-6} and 1.63 x 10^{-6} kg Ethene-equiv./kWh, respectively), which is 29.3% less. Contributions to the environmental impact categories are discussed in order below to determine the factors in the EPR's life cycle which means that all environmental impacts are reduced.

7.2.3.2.4 Material recyclability

The material recyclability of the EPR is estimated to be around 81.3% (when averaging the recyclable materials used in construction by weight). The EPR is again (similarly to the

AP1000 and nuclear power reactors generally) composed proportionally of a high amount of concrete, which has a recyclability rate of around 80% (Stamford, 2012). The various metals also used in construction display 100% recyclability (Stamford, 2012). Therefore, the total rate of recyclability of components of the EPR is close to 80% as 93% of the EPR is composed of concrete (and as the EPR has proportionally more concrete than the AP1000 its recyclability is slightly lower).

7.2.3.2.5 Water eco-toxicity

The freshwater eco-toxicity potential values for the EPR, Sizewell B and UK PWR 1.65 x 10^{-2}, 2.08 x 10^{-2} and 2.17 x 10^{-2} kg DCB-equiv./kWh, respectively. The FETP result for the EPR is 20.7% lower than the result for Sizewell B and 24.2% lower than the result for a generic UK PWR. The majority of the impact of this indicator for the EPR comes from the milling life cycle stage (86.5%) and the mining of uranium (6.5%). The EPR FETP result is lower than the value for Sizewell B as less construction materials are used to build the EPR compared to Sizewell B, and in addition, the front end of the fuel cycle displays a slightly lower impact for the EPR as less uranium (17% less) is needed to generate the same amount of electricity. The difference in impact for the EPR’s FETP compared to a generic UK PWR is also due to more construction materials used and uranium use in the model of a generic PWR and in addition, the FETP for the enrichment life cycle stage for the generic PWR is much higher that the EPR (a 97% reduction from the PWR FETP) as the UK PWR model specifies to types of enrichment for the uranium enrichment life cycle stage – 60% of the uranium is enriched at the EURODIF enrichment facility and 40% at the URENCO enrichment facility. Both the EPR and Sizewell B models specify that all enrichment takes place at the URENCO enrichment facility. The difference is mostly attributable to the use of diffusion enrichment at the EURODIF facility, whereas the URENCO facility uses centrifugal enrichment. The life cycle impacts by life cycle stage are displayed in Figure 7.20.

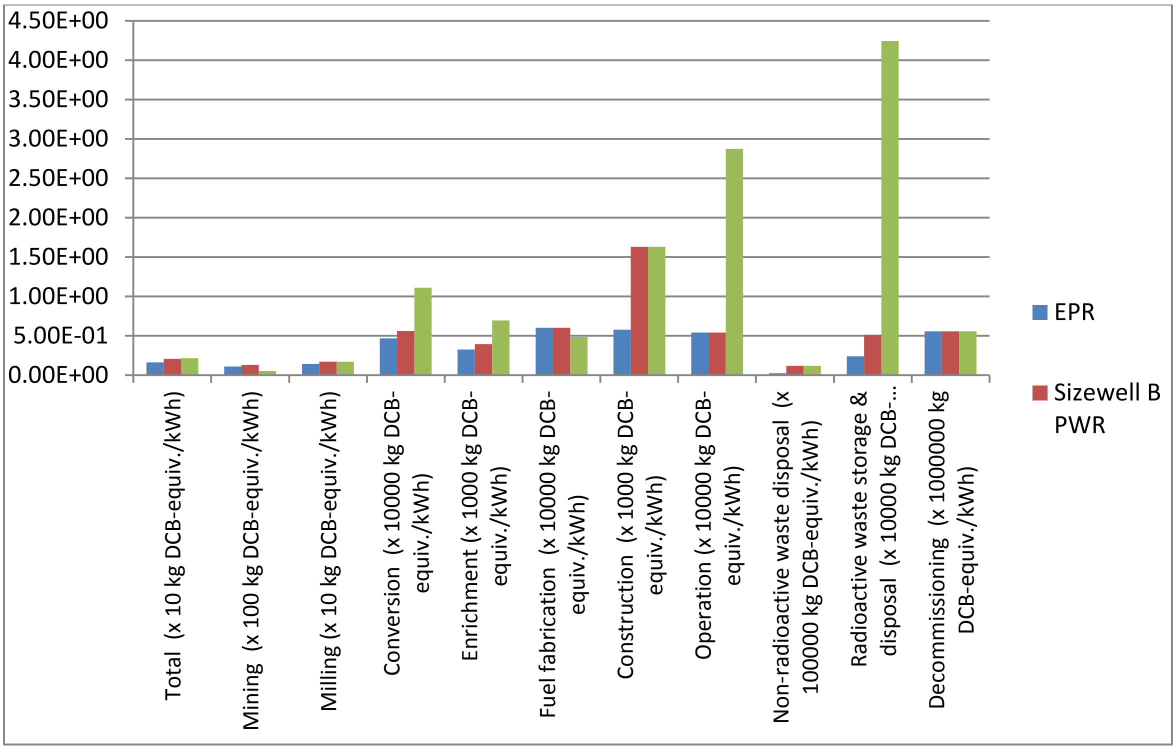


Figure 7.20. Freshwater eco-toxicity potential (FAEP) life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

The marine eco-toxicity values for the three modelled nuclear reactors are as follows: EPR - 32.6 kg DCB-equiv./kWh; Sizewell B – 40.3 kg DCB-equiv./kWh and UK PWR – 43.7 kg DCB-equiv./kWh. The majority of the marine eco-toxicity (METP) result for the EPR life cycle comes from the milling process (85%), followed by power plant construction (5%). This can be seen in Figure 7.21. The EPR METP result is lower than the result for Sizewell B primarily due to fewer materials used in the construction of EPR reactors and because less uranium is used in the EPR. Again, the METP result is lower for the EPR compared to a generic UK PWR due to a larger amount of construction materials used in PWRs, the lower use of uranium and also due to the differences in the types of uranium enrichment used.

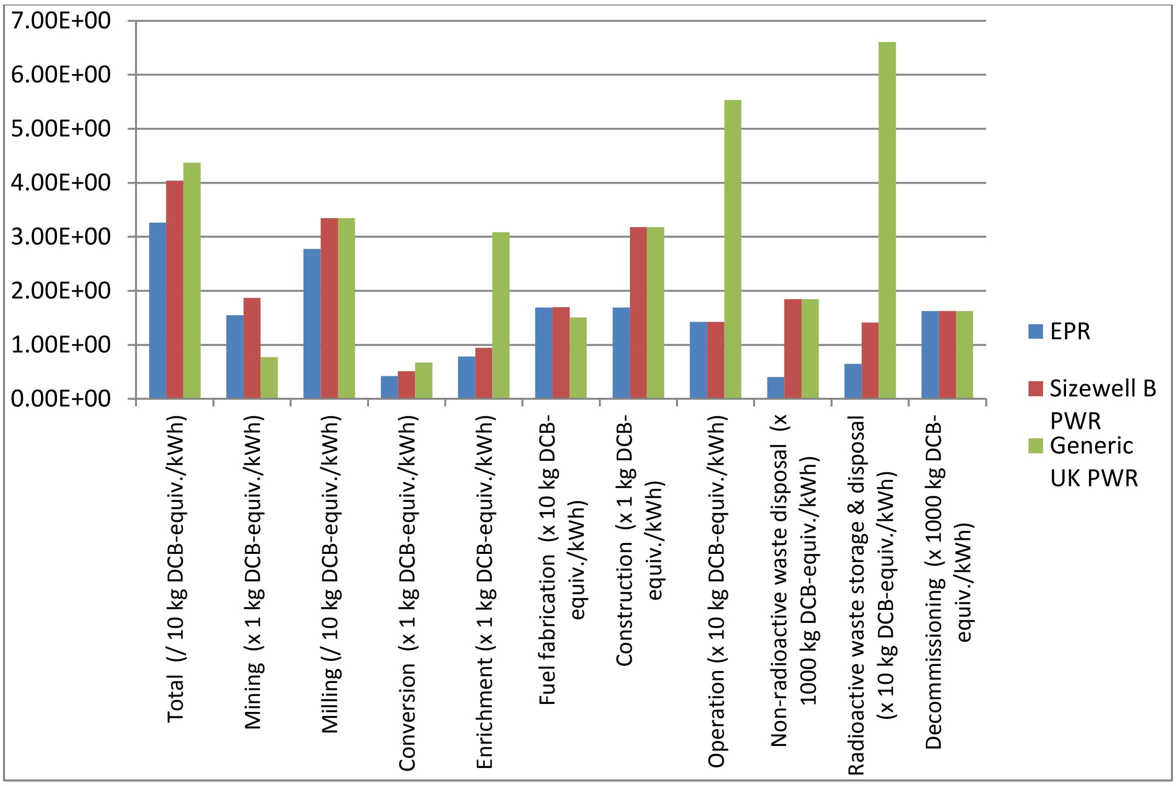


Figure 7.21. Marine eco-toxicity potential (MAEP) life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.3.2.6 Global warming potential

The GWP of the EPR is 5.12 x 10^{-2} kg CO_2-equivalent/kWh, compared to 6.38 x 10^{-2} kg CO_2-equivalent/kWh for Sizewell B and 6.86 x 10^{-2} kg CO_2-equivalent/kWh for the generic PWR. The EPR displays savings on global warming potential (GWP) of 19.8% and 25.4% when compared to older, Generation II PWRs (Sizewell B and a generic PWR modelled under UK conditions, respectively). This new information about the life cycle impacts of the EPR and its lower contribution to GWP (compared to Generation II PWRs) informs the debate on new nuclear power compared to competing options - especially when many Government energy decisions are based on the carbon emissions of different energy options.

Compared to Sizewell B, the savings in GWP for the EPR occur in the construction, conversion, enrichment, mining, milling, waste disposal and radioactive waste disposal phases of the life cycle (see Figure 7.22). The front end of the life cycle of the EPR differs from Sizewell B, as 17% less uranium is used per kWh of electricity generated. The EPR has a lower GWP impact for radioactive waste storage and disposal when compared to the Sizewell B model. This is due to the lower estimated levels of spent fuel arising from the EPR operation that need to be conditioned and stored in final repository as less uranium is per kWh electricity generation.

The impact GWP impacts for the EPR reactor are on average 25.4% lower than the generic PWR. The main saving for GWP in the EPR model compared to the UK PWR is due to less materials needed in construction and operation and also because only centrifugal enrichment is used in the EPR model (60% diffusion enrichment is used in the generic UK PWR model). Despite the overall saving in GWP for the EPR model, the EPR exhibits larger GWP under the fuel fabrication and mining life cycle stages. The reduction in GWP for radioactive waste storage for the EPR is described in the above paragraph. The fuel fabrication GWP impact is higher under the EPR due to the German electricity mix specified; a generic European mix is specified in the generic UK PWR model. The mining GWP impact is larger for the EPR as more uranium is sourced from underground mining than open pit mining (60% for underground and 40% for open pit).

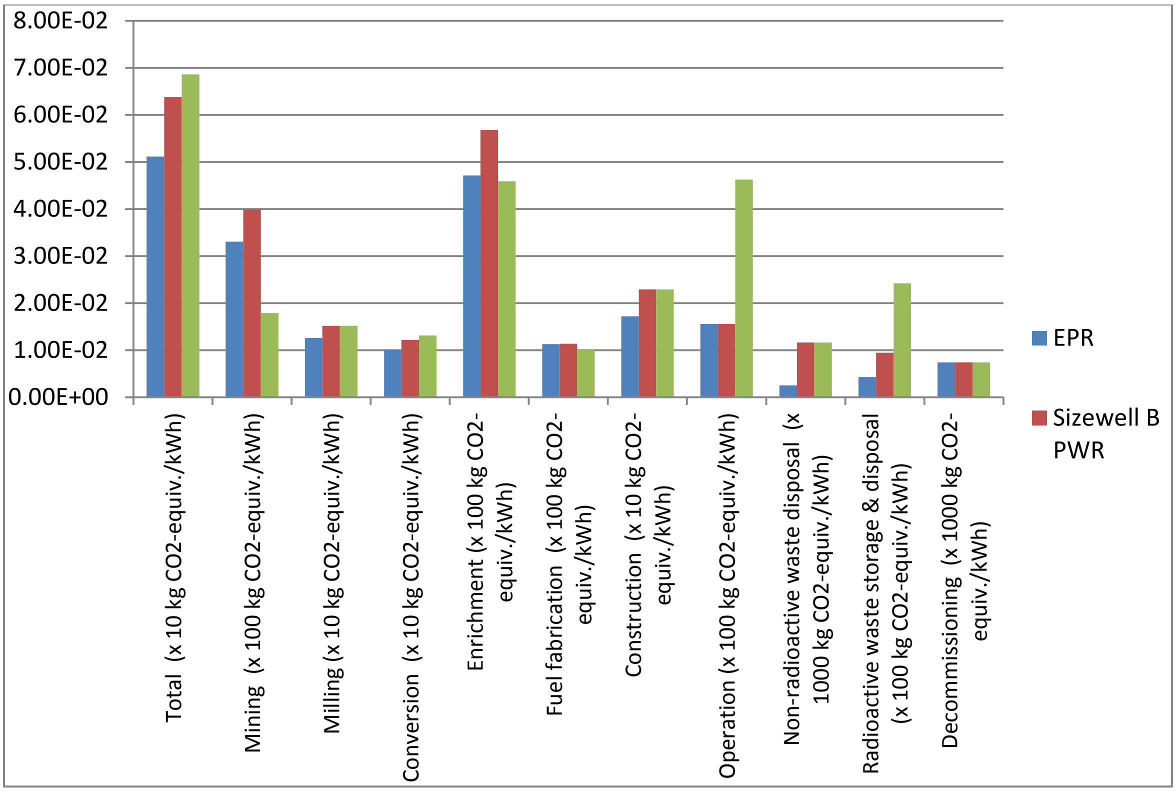


Figure 7.22. Global warming potential (GWP) life cycle impact of the European Pressurised Reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.3.2.7 Ozone layer depletion potential

The ozone layer depletion potential (ODP) for the EPR is 4.34 x 10^{-10} kg R11-equivalent/kWh and 18.4% lower than the impact for Sizewell B (5.32 kg R11-equivalent/kWh) and 26.4% lower than the impact for a generic UK PWR (5.9 kg R11-equivalent/kWh). From analysis of the EPR life cycle, it can be observed that 30.7% of the ODP comes from the conversion stage and 30.7% from the milling stage. Compared to the ODP in the UK PWR model, savings on ODP are observed in the EPR’s construction, conversion, enrichment, milling, waste disposal, radioactive waste disposal and operation life cycle stages. The EPR also makes savings in ODP compared to Sizewell B under the mining life cycle stage.

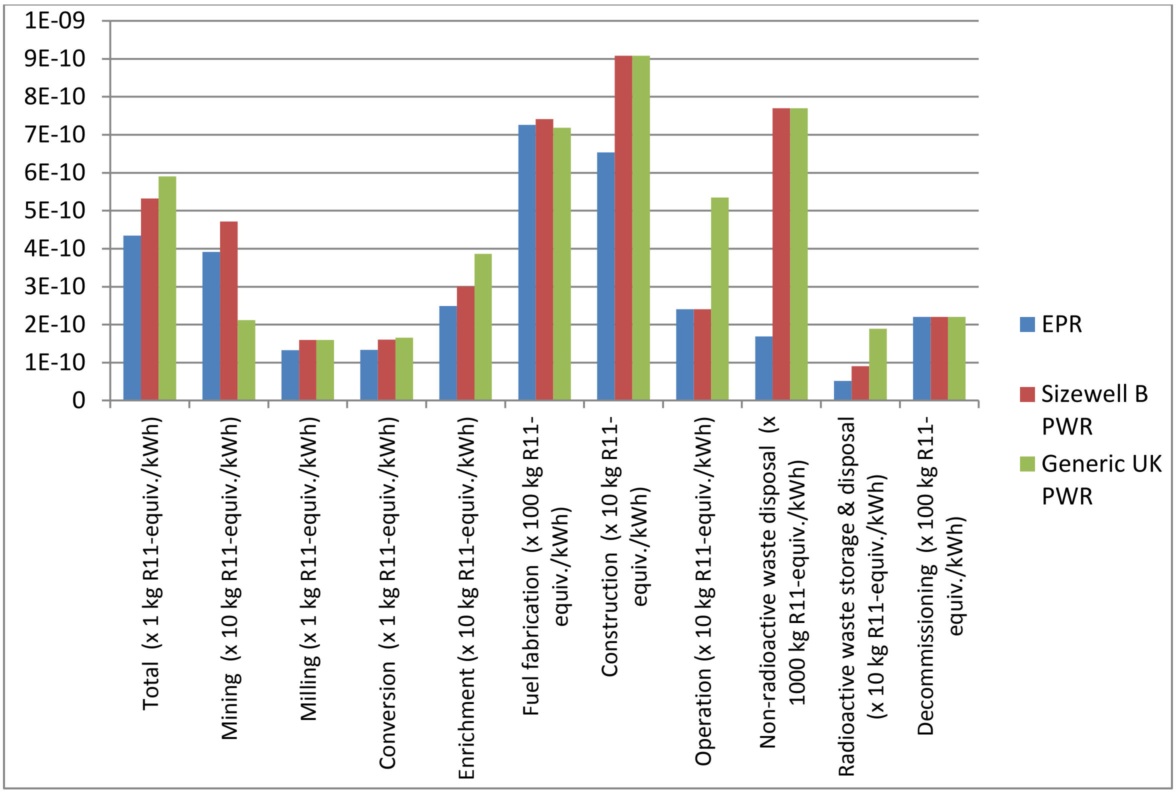


Figure 7.23. Ozone layer depletion potential (ODP) life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.3.2.8 Acidification potential

The acidification potential impacts for the three reactors compared within this section are as follows: EPR – 3.53 x 10^{-5} kg SO_2-equivalent/kWh; Sizewell B – 4.38 x 10^{-5} kg SO_2-equivalent/kWh; and the generic PWR – 4.91 x 10^{-5} kg SO_2-equivalent/kWh. The AP for the EPR is 19.4% lower than that for Sizewell B and 28.2% lower than the AP for the UK PWR. The main contribution of the acidification potential for the EPR comes from the milling stage of the life cycle (51.3%), this can be seen in Figure 7.24. In the Sizewell B and UK PWR life cycles, 49.5% and 44.3% comes from milling, respectively. The EPR has a lower AP due to less materials being used in construction compared to both Sizewell B and the UK generic PWR and also due to the enrichment methods used in the EPR model (which is the same method as used for Sizewell B).

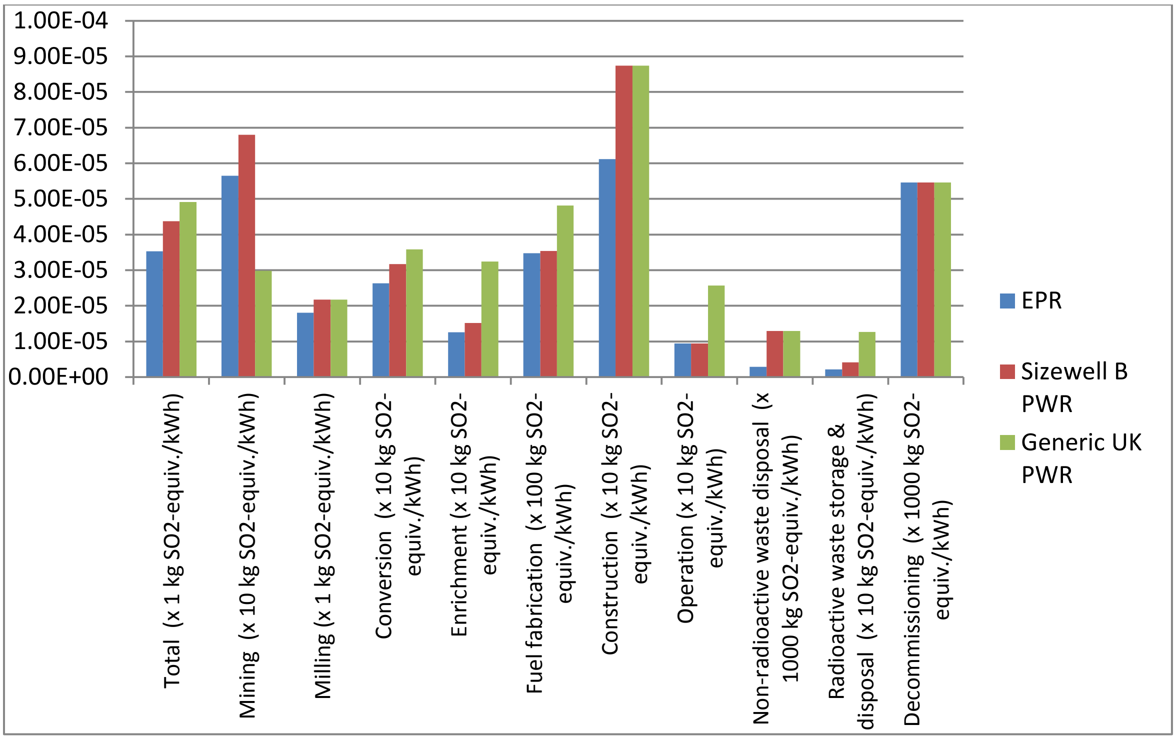


Figure 7.24. Acidification potential (AP) life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.3.2.9 Eutrophication potential

The eutrophication potential (EP) for the EPR life cycle is 1.12 x 10^{-5} kg phosphate-equivalent/kWh, which is 22.1% lower than Sizewell B (1.44 x 10^{-5} kg phosphate-equivalent/kWh) and 26% lower than UK generic PWR (1.52 x 10^{-5} kg phosphate-equivalent/kWh) life cycles. For the EPR, the contribution to EP comes mainly from milling of uranium (41.8%) and construction (21%), which can be seen in Figure 7.25. The Sizewell B model shows that milling is also the highest contributor to EP at 39% of the life cycle impact, and also for the UK generic PWR (37%). The differences in EP between the reactors are due to the construction stage of the EPR as fewer materials are used to build the reactor.

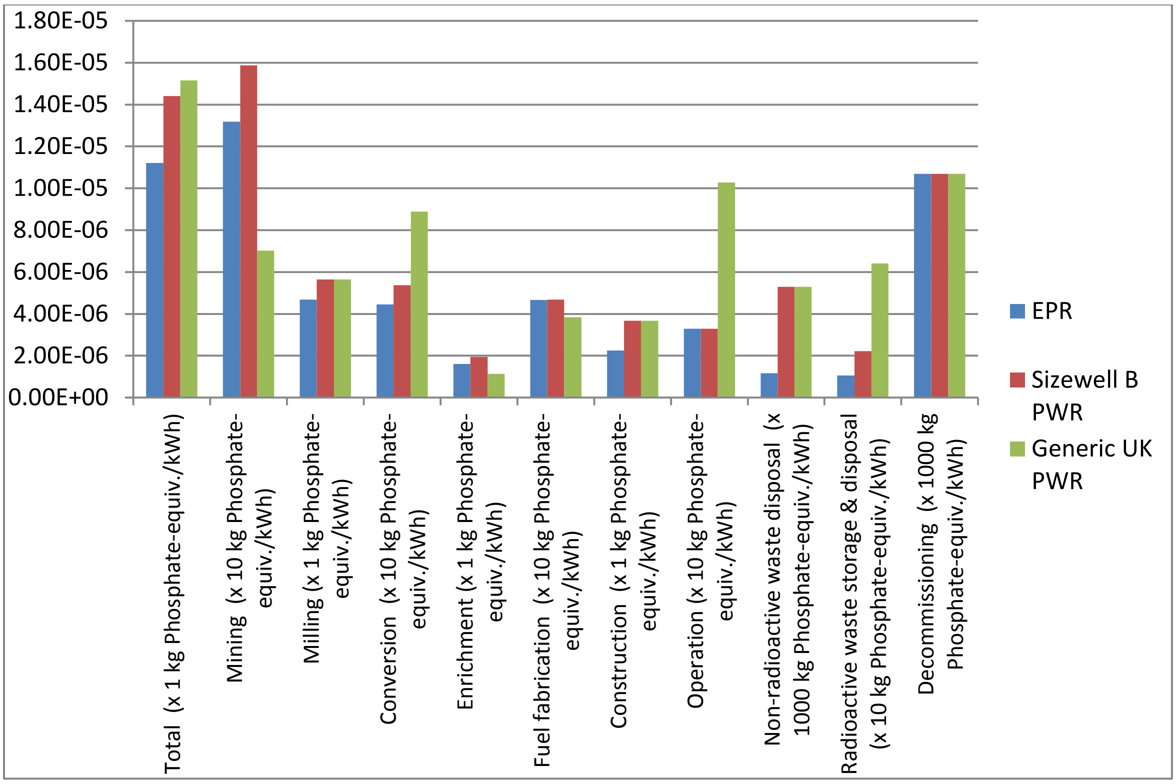


Figure 7.25. Eutrophication potential (EP) life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.3.2.10 Photochemical smog creation potential

The photochemical smog potential impacts for the EPR, Sizewell B and EPR are 1.63, 2.07 and 2.3 x 10^{-6} kg ethane-equivalent, respectively. The POCP result for the EPR is 21.4% lower than the value for Sizewell B and 29.3% lower than the value for the UK PWR. The main life cycle contribution to POCP in the EPR is the milling stage (46.5%) (see Figure 7.26). For the Sizewell B and PWR models, milling is also the largest contribution over both of their life cycles at 44.5% and 39.7%, respectively. Again, the main reason why the POCP vale for the EPR is lower than those for Sizewell B and the UK PWR is due to the construction stage of its life cycle.

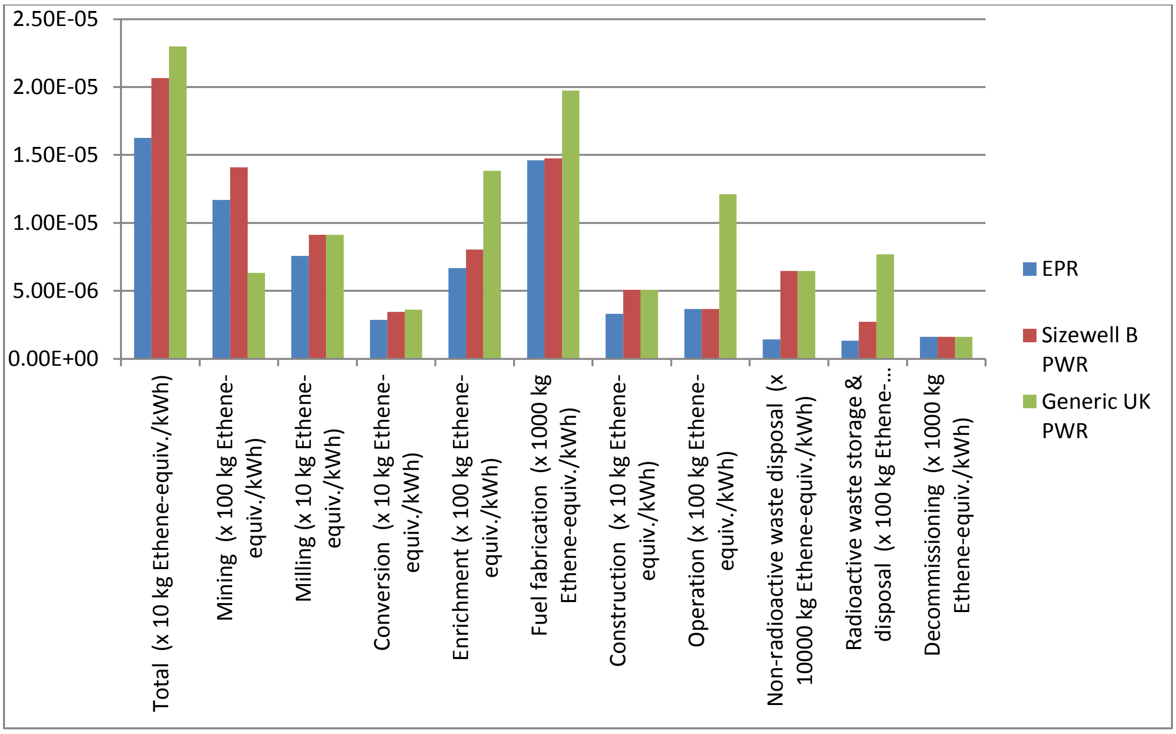


Figure 7.26. Photochemical smog creation potential (POCP) life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.3.2.11 Land use and quality

Land occupation for the EPR is 4.6 x 10^{-4}, 5.1 x 10^{-4} for Sizewell B and 5.6 x 10^{-4} for the UK generic PWR. This is an increase of 11.4% land occupation for Sizewell B from the EPR and an 18.5% increase from the EPR value compared to the UK PWR (see Figure 7.27). The difference in land occupation for the three reactors is attributed mostly to the construction, conversion and enrichment. For the EPR, land occupation for construction of the power station contributes 62% to this indicator. The increase in the absolute value for land occupation for Sizewell B and the UK PWR is therefore mostly due to the increased construction needs for those reactors.

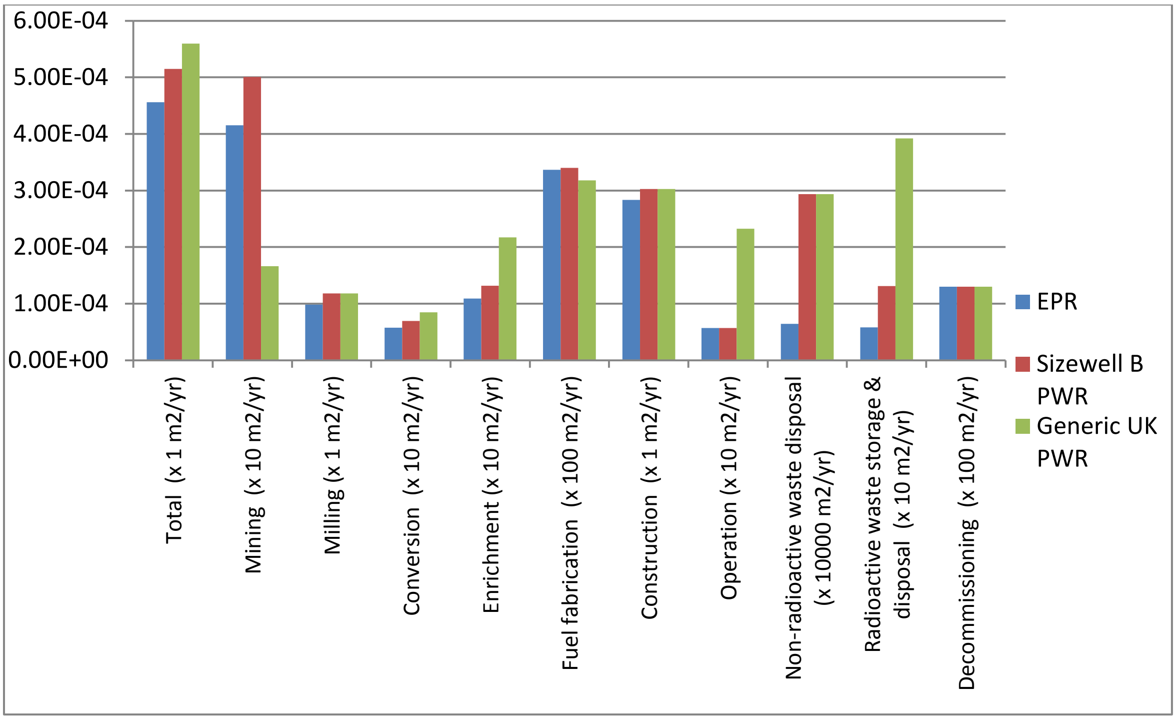


Figure 7.27. Land occupation life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

EDF Energy own land adjacent to five nuclear power plant sites in the UK. These sites include: Bradwell, Essex; Hartlepool; Heysham, Lancashire; Hinkley Point, Somerset; and Sizewell, Suffolk. At present, planning is only being sought for the Hinkley Point and Sizewell nuclear sites. However, the other sites are likely to be licensed in due course of the Generic Design Assessment process and planning applications. The Bradwell site in Essex is to be sold off by EDF; this is being enforced due to utility competition law in the UK (I-Nuclear, 2012). Therefore, EDF has a potential to operate new nuclear power stations on the remaining four sites. All but one of these four sites are located on greenfield land (the Hartlepool site is located on industrial land surrounding the existing nuclear power station). Therefore, the greenfield land use for the EPR (based on the four sites owned by EDF) would be 75% (as three out of the four sites are located on greenfield land, and one is located on brownfield land).

The terrestrial eco-toxicity potential (TETP) for the EPR is 3.26 x 10^{-4} kg DCB-equivalent, which is 18.7% lower than Sizewell B (4.01 x 10^{-4} kg DCB-equivalent) and 21.9% lower than the value for the UK PWR (4.17 x 10^{-4} kg DCB-equivalent). TETP for the EPR life cycle is attributed mostly to the milling stage (91%). The Sizewell B life cycle shows that

92.5% of its TETP comes from the milling stage and the generic UK PWR shows that 93% of its TETP impact also comes from the milling life cycle stage. This can be seen in Figure 7.28. An increase in TETP for Sizewell B and the UK PWR comes from the extra materials used in construction compared to the EPR reactor. The enrichment stage of the EPR and Sizewell B also exhibit lower TETP values than the UK PWR, due to the use of only diffusion enrichment rather than a mixture of diffusion and centrifugal, which is specified in the UK PWR model.

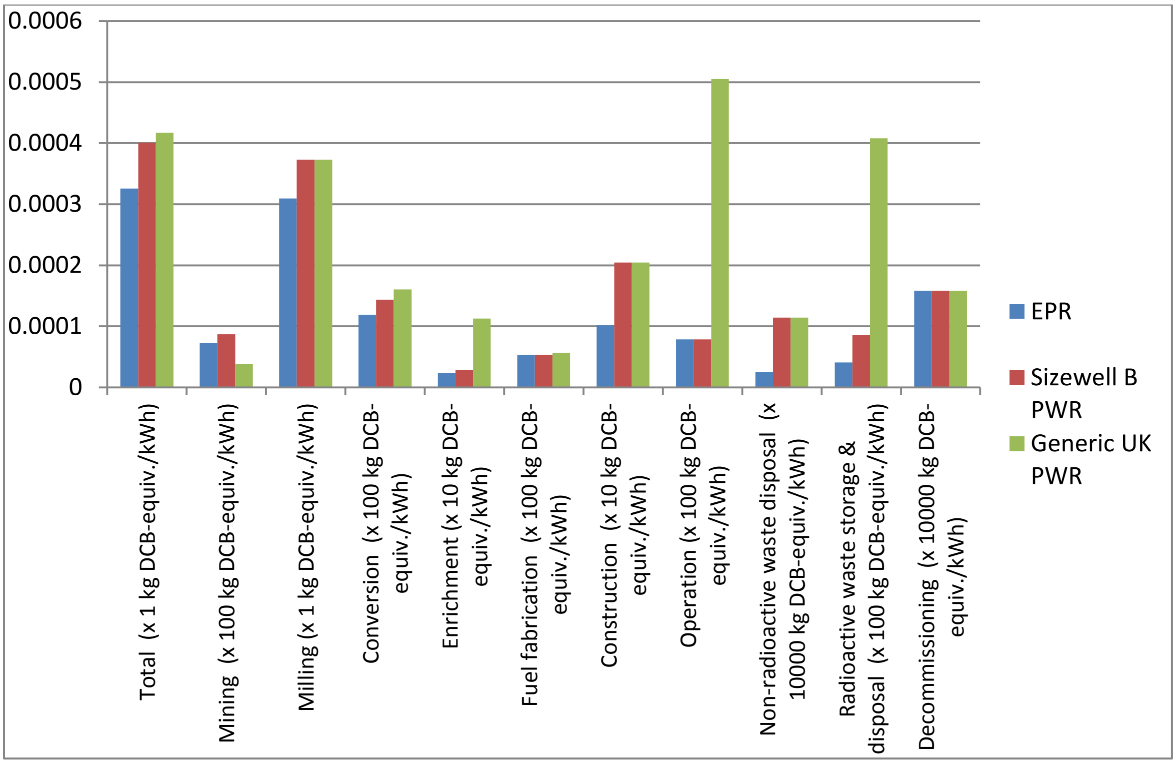


Figure 7.28. Terrestrial eco-toxicity potential (TEP) life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.3.2.12 Comparison and validation of the EPR results

The LCA results of the EPR nuclear reactor modelled in this work are compared here to two EPRs modelled from NEEDS (2008), which are presented in a paper by Simons and Bauer (2012). As far as the author of this thesis is aware, there are no studies that display LCA results for the EPR specific to operation in the UK. The paper by Simons and Bauer (2012) does not report the full LCA suite of impacts that are presented as part of this thesis, but it does report global warming potential and fossil fuel usage. Other indicators assessed in the paper by Simons and Bauer are not directly comparable to this work as they take into account varied methodologies which are not concordant with those used in the LCA methodology used in this thesis. Here, the results of the EPR GWP and fossil fuel usage impacts from NEEDS are compared to the results of the EPR life cycle modelled within this work.

The results are compared on the basis of the functional unit, ‘1 kWh’. Results of a life cycle assessment carried out on the EPR for the year 2030, operating in France and Switzerland displayed values of 4.4 and 4.8 g CO_2-equivalent/kWh, respectively (Simons and Bauer, 2012), which displays some concordance with the GWP value of 5.12 g CO_2-equivalent/kWh calculated for the EPR as part of this work. Fossil fuel usage values for the French and Swiss operated EPRs are 0.018 and 0.02 MJ-equivalent/MJe (0.005 and 0.006 MJ-equivalent/kWh), which are comparable to the fossil fuel depletion rate of 0.069 MJ calculated for the UK EPR within section 7.2.3.3.8 of this thesis. The differences in assumptions that Simons and Bauer make for EPR operation in 2030 in France and Switzerland include: a closed fuel cycle for the French EPR; an open fuel cycle for the Swiss EPR; burn-up of 60 GW d/tU; and a European electricity mix for all background processes, which displays a significantly lower GHG intensity than the 2005 European electricity mix (an average 500 g CO_2/kWh in 2005 compared to 350 g CO_2/kWh in 2030). These differences in model specification may account for the differences displayed between the EPR modelled within this thesis and those modelled by Simons and Bauer (2012).

7.2.3.3 Social sustainability

The results of the social sustainability assessment are discussed below under the following headings of the social sustainability issues: provision of employment; human health impacts; large accident risk; local community impacts; human rights and corruption; energy security; nuclear proliferation; and intergenerational equity.

7.2.3.3.1 Provision of employment

Provision of employment is measured through the use of two indicators: direct employment; and total employment (which encompasses direct and indirect employment).

Direct employment is a measure of employment created across the whole life cycle of power generation. Total employment is a sum of direct employment and indirect employment, which measures employment created across supply chains which exist because of an electricity-generating installation's operation.

Data on the employment for the EPR have been used from the thesis of Stamford (2012). Although some aspects of the values used will be overestimations (i.e. the EPR is more technically efficient and therefore likely to employ fewer people), the value used is likely to be a good approximation of employment in the EPR life cycle. Direct employment and total employment values of 56 person-years/TWh and 81 person-years/TWh respectively are assumed for the fast reactor.

7.2.3.3.2 Human health impacts

Human health impacts are measured by three indicators: worker fatalities; human toxicity potential; and human health impacts from radiation. The latter two indicators are calculated using the CML methodology in the GaBi LCA software over the whole life cycle of electricity generation. Human toxicity potential is a measure of substances that could potentially harm humans, such as heavy metals. Human health impacts from radiation is a measure of the effect of radiation on the population expressed in disability adjusted life years (DALY).

Human health impacts from toxic substances

Over the whole life cycle, the EPR reactor has a human toxicity potential that is 20.6% lower than the HTP for Sizewell B power station and 24.7% lower than the HTP for the generic UK PWR (per kWh the EPR has a HTP of 0.089 kg DCB-equivalent, Sizewell B has a HTP of 0.112 kg DCB-equivalent per kWh and the generic UK PWR has a HTP of 0.118 kg DCB-equivalent per kWh). Figure 7.29 displays the life cycle impacts of the three nuclear reactors, broken down by life cycle stage.

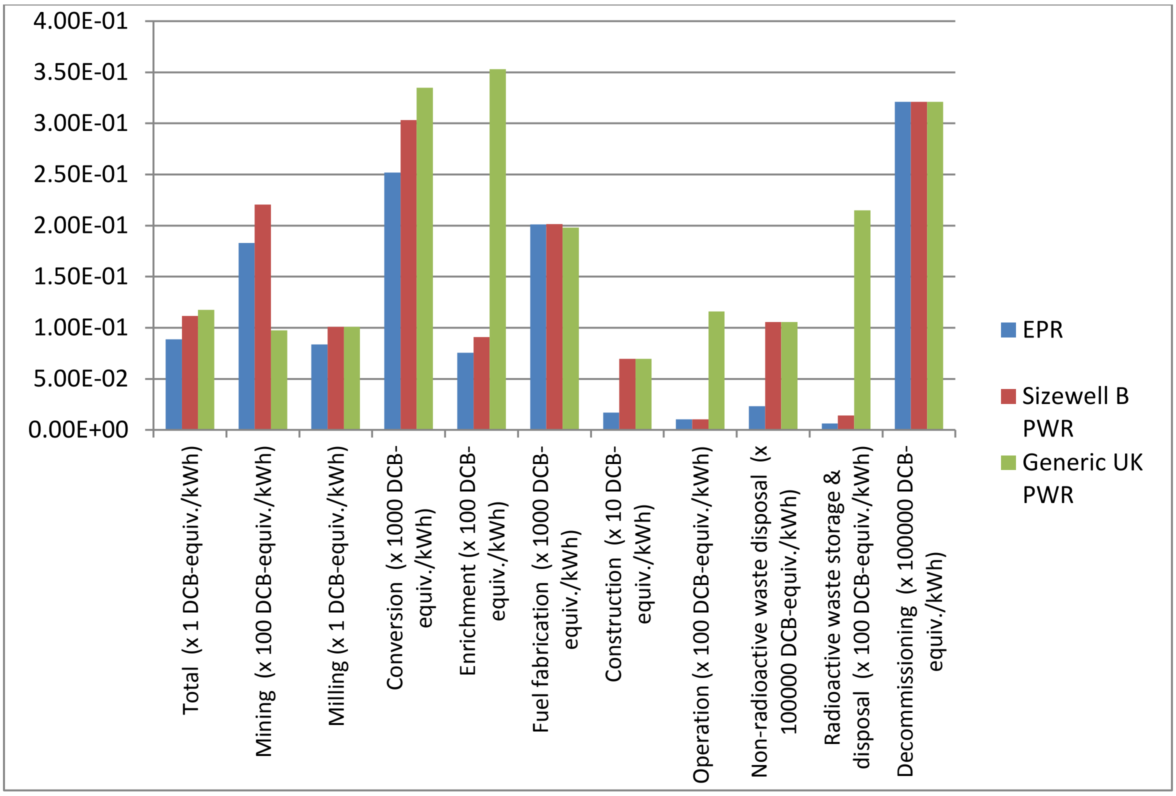


Figure 7.29. Human toxicity potential (HTP) life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Human health impacts from radiation

Human health impacts from radiation total 1.7 x 10^{-8} DALY per kWh for the EPR reactor, 2.02 x 10^{-8} DALY per kWh for Sizewell B and 2.43 x 10^{-8} DALY per kWh for the generic UK PWR over the whole life cycle. The EPR reactor has a human health impact from radiation that is 15.7% less than that for Sizewell B and has an impact 30% lower than that for generic UK PWR. Figure 7.30 displays the life cycle impacts of the EPR, Sizewell B and generic UK PWR reactors, broken down by life cycle stage.

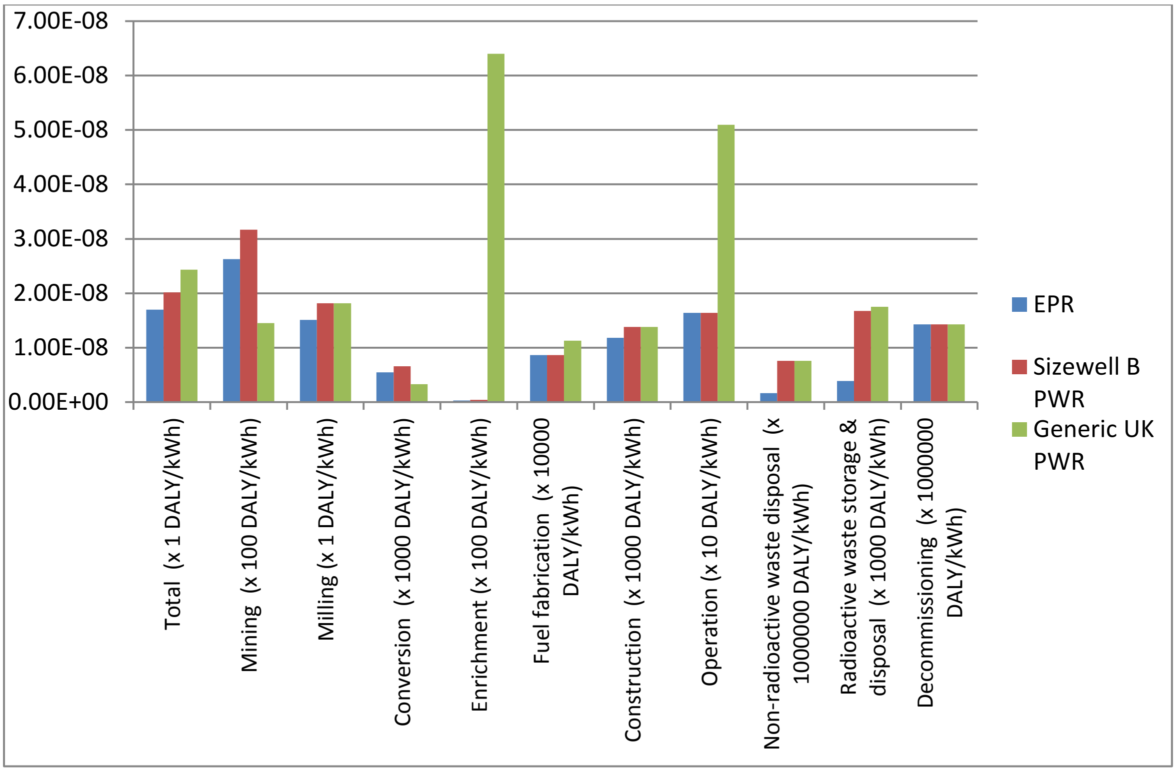


Figure 7.30. Human health impacts from radiation life cycle impact of the EPR reactor, Sizewell B reactor and a generic PWR modelled under UK-specific conditions, broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.3.3.3 Large accident risk

This measure of large accident risk is calculated from the loss of life due to large accidents associated with a particular technology. The perspective of this measurement is partly historical, with data used from the OECD's reporting and also partly on probabilistic safety assessments.

The estimate of potential fatalities from operation of the EPR reactor have been calculated using the Probabilistic Safety Assessment of the EPR (Areva NP and EDF, 2011), which describes the overall risk of containment failure resulting in accidents when in power and when shutdown. The total power output of the EPR reactor over its lifetime and its total operating life are also used to calculate the number of estimated fatalities for this reactor. The total number of deaths that would occur due to a large accident are then calculated by using historical data from the Chernobyl disaster, which has been the largest nuclear accident in history in terms of the number of fatalities resulting from this accident. Several estimates are available for the total number of deaths that occurred as a result of the disaster, but it is widely accepted that between 31-46 deaths happened in the immediate aftermath of the accident (IAEA, 2006). Due the large variation in deaths attributed to the Chernobyl disaster, an upper and lower estimate of large accident fatalities have been calculated for the EPR reactor, which are 1.19 x 10^{-12} and 5.93 x 10^{-12} fatalities/kWh.

7.2.3.3.4 Local community impacts

As stated earlier in this chapter, the local community impacts are not calculated for the technologies assessed in this chapter.

7.2.3.3.5 Human rights and corruption

Countries involved in the life cycle stages of nuclear power that is generated in the UK currently include: Namibia (uranium mining), Australia (uranium mining), France (uranium refinement and conversion), Germany (enrichment and fuel fabrication) and the UK (operation and waste disposal). Although the sourcing and production of fuel and materials may vary depending on the power plant operating country, this is, at the current time impossible to determine. Therefore, current uranium sourcing and fuel production life cycle stages taken from a life cycle assessment of the Sizewell B power station are used (BE, 2008). This gives an average Corruptions Perceptions Index of 7.2 (Transparency International, 2011).

7.2.3.3.6 Energy security

Amount of fossil fuel potentially avoided

This indicator is a calculation of the amount of fossil fuel that would have to be combusted in order to provide an equivalent amount of electricity from a non-fossil fuel source (in this case, the EPR reactor). Stamford and Azapagic (2011) determined that 1 kWh of electricity from the UK’s current fossil fuel fleet would require 0.2 kg of oil equivalent.

Diversity of fuel supply

The diversity of the UK’s nuclear fuel supply for use in the EPR reactor is again calculated by using Simpson’s Index of Diversity (SID) (see Stamford and Azapagic, 2011 for method of calculation), which calculates an index of diversity based on the richness of the supply of fuel (i.e. the number of suppliers) and the evenness of that supply spread between each supplier. The calculated SID is then used to determine the diversity of fuel supply (DFS) through multiplication this value by the proportion of fuel supplied from imports, added to the supply of fuel that is provided indigenously. The overall DFS for uranium nuclear fuel in the UK would be 0.86 (Stamford and Azapagic, 2012), with a score of 1 representing a diverse fully supply and a score of 0 representing a fuel supply that is overly reliant on one nation for its supplies.

Fuel storage capability

This indicator is expressed in terms of energy content of the fuel per unit mass of fuel stored. This indicates fuel storage needs for different types of fuels. The energy density of uranium fuel for thermal reactors has been calculated to be 10 million GJ/m^3, assuming a burn-up of 50 GW d/tU (Stamford and Azapagic, 2011).

7.2.3.3.7 Nuclear proliferation

The measure of nuclear proliferation of nuclear technologies is measured using three components to this indicator: use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; and requirement for enriched uranium. The first criterion addresses the ease at which weapons usable spent fuel may be extracted from nuclear reactors. Pressurised water reactors (like the EPR) are not able to refuel online due to the necessary shut down of the reactor and extraction of the water from the pressure vessel. Enriched uranium is needed to produce fuel for the PWR fuel cycle. Reprocessed fuel can be used in the EPR, but the current UK energy policy is not to used processed fuel in its thermal reactors. Therefore, the EPR reactor scores one out of a maximum three for nuclear proliferation potential using the above measures.

7.2.3.3.8 Intergenerational equity

Intergenerational equity is defined as problems created for future generations to manage. Depletion of resources and long-lived hazardous waste are obvious issues associated with future generations. Climate change is another issue that will affect people many generations into the future, however, this issue is addressed under the global warming potential indicator under the environmental set of measures. Here, intergenerational equity is defined through the use of several measures: use of abiotic elemental resources; use of abiotic fossil resources; volume of radioactive waste to be stored; and volume of liquid CO_2 to be stored.

Use of abiotic elemental resources

Over the whole life cycle, the EPR reactor uses elemental abiotic resources 18.4% less than the impact for Sizewell B power station and 23.8% less than the generic UK PWR (per kWh the EPR depletes elemental abiotic resources at a rate of 3.62 x 10^{-5} kg Sb-equivalent, Sizewell B has an impact of 4.44 x 10^{-5} kg Sb-equivalent per kWh and the generic UK PWR has an impact of 4.76 x 10^{-5} kg Sb-equivalent per kWh). Figure 7.31 displays the life cycle impacts of the three nuclear reactors, broken down by life cycle stage.

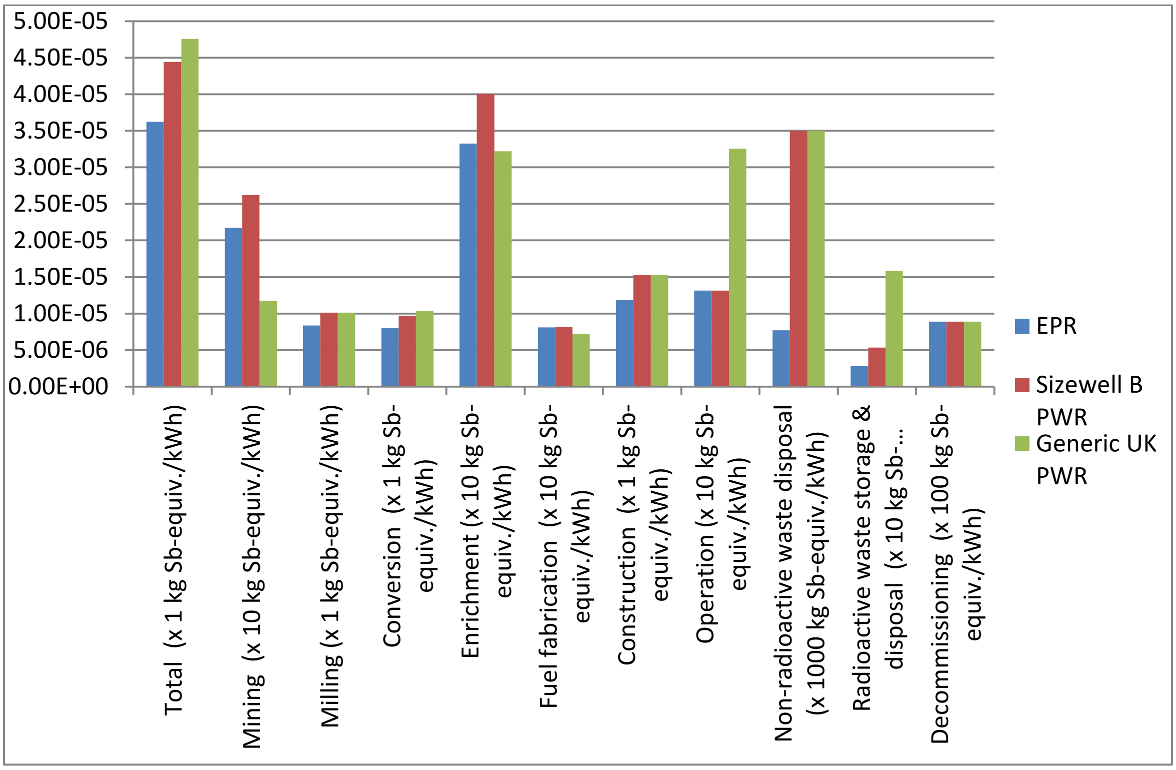


Figure 7.31. Use of abiotic elemental resources life cycle impacts of the EPR reactor, Sizewell B and a generic UK PWR broken down by life cycle stage. [Where division and multiplication symbols are seen within the labels this means that the value of these indicators have either been divided or multiplied by the number specified in order to scale the value in line to other indicators on the graph.]

Use of abiotic fossil fuel resources

Over the whole life cycle, the EPR reactor uses abiotic fossil resources 18.1% less than the impact for Sizewell B power station and 24.2% less than the generic UK PWR (per kWh the EPR depletes abiotic fossil resources at a rate of 0.069 MJ, Sizewell B has an impact of 0.084 MJ per kWh and the generic UK PWR has an impact of 0.091 MJ per kWh). Figure 7.32 displays the life cycle impacts of the three nuclear reactors, broken down by life cycle stage.

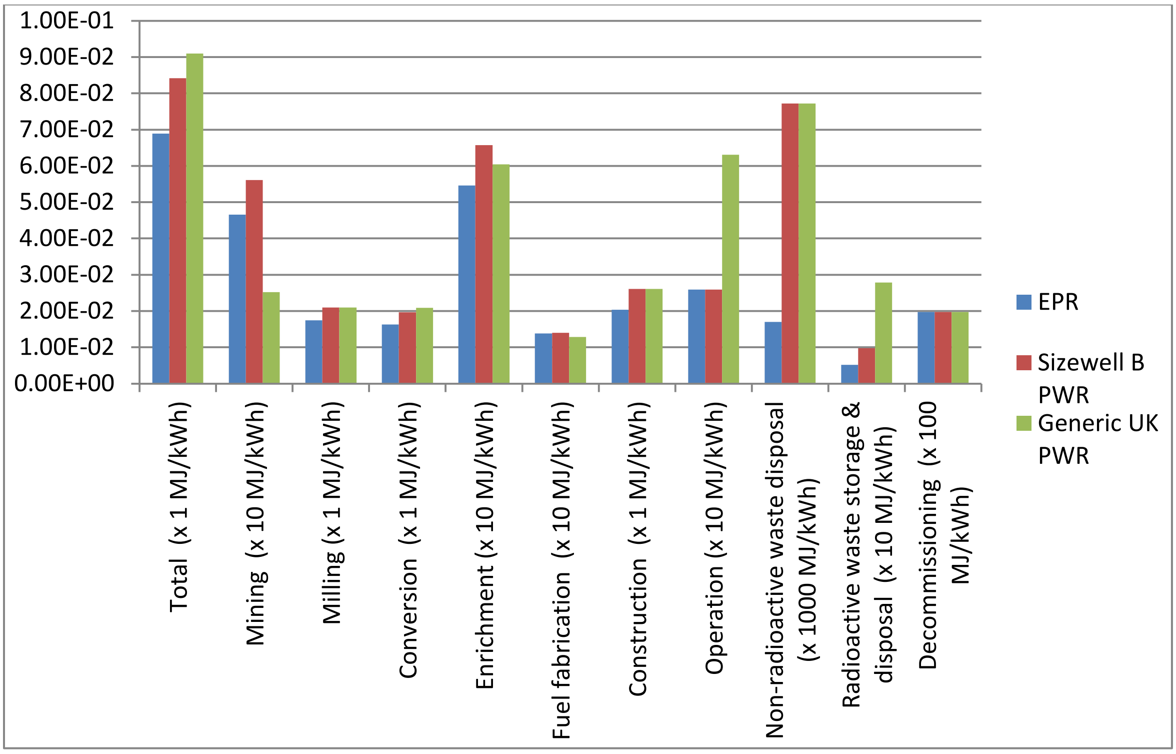


Figure 7.32. Use of fossil fuel resources life cycle impacts of the EPR reactor, Sizewell B and a generic UK PWR broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Radioactive waste to be stored

The radioactive waste to be stored value is taken from Stamford (2012). A value of 1.2 m^3/TWh is assumed (Stamford, 2012).

7.2.4 Assessment of the sustainability of fast breeder reactor technologies

7.2.4.1 Techno-economic sustainability

The results of the techno-economic sustainability assessment are discussed under the following headings of the techno-economic issues: operability; technological lock-in; immediacy; levelised cost of generation; cost variability; and financial incentives.

7.2.4.1.1 Operability

There are very few data on capacity factors for fast breeder reactors. However, data is available on the French Superphénix (sodium) fast reactor's capacity factor over the period that it operated from 1985 to 1996. The capacity factor for Superphénix over this time was on average 7.8% (IAEA, 2012b). This capacity factor is very low compared to modern thermal nuclear reactors, which typically have capacity factors of between 50-86% (Stamford and Azapagic, 2011). There are also very few fast reactors that have operated commercially in order to gauge potential operation levels of operability to. The UK's Dounreay reactor also displayed a low load factor of 26.9% over the lifetime of operation, which is also indicative of a low capacity factor (IAEA, 2012b). The reason for the low capacity factors of the Superphénix and Dounreay reactors is due to long periods of maintenance and repair that were undertaken on both of these reactors during their operational lifetimes and were hence unreliable forms of electricity generation. For example, the Superphénix and Dounreay reactors both suffered significant sodium leaks and some of these leaks results in serious fires (IPFM, 2010). It is unrealistic to assume that any future fast breeder reactors built would have such a low capacity factor as it is likely that lessons learned from previous fast reactors would be factored in to the building of new reactors and therefore the capacity factor would be likely to be much closer to that of modern thermal reactors.

There are also very few data available on the availability factor of fast reactors. Again, in this case data have been used from the French Superphénix fast reactor's operation over the period from 1985 to 1996. The availability factor of the Superphénix reactor was, on average, 9% (IAEA, 2012b). This is again very low compared to more modern thermal reactors and is due to the long periods of maintenance and repair that were undertaken as a result of many sodium coolant leaks and resultant fires from these leaks. Other fast breeders have also displayed low availability factors over their lifetimes, for example, India's Fast Breeder Test Reactor had an availability factor of 20% due to accidents and unusual occurrences (IAEA, 2002).

Technical dispatchability comprises: ramp-up rate, ramp-down rate, minimum up time and minimum down-time. Data for the four measures for technical dispatchability for fast reactors have not been found for this study. In the absence of any other data, values for current day pressurised water reactors are used instead. These estimates are likely to be overestimates due to the difference in the maturity of the technologies. Nevertheless, a ramp-up rate, ramp-down rate, minimum up time and minimum down time of 0.17 (%/min), 0.83 (%/min), 999 (mins) and 999 (mins) respectively are assumed for the fast reactor (Stamford and Azapagic, 2012).

The ratio of capital cost to total levelised cost for fast breeder reactors has been determined by using the cost data determined for fast breeder reactors – see section on levelised costs below. The data for total levelised costs have been calculated using the NEEDS factors applied to the costs of each life cycle stage (NEEDS, 2007 Dec). NEEDS estimated that the European Fast Reactor investment costs are 30% higher than those for a typical PWR. Operation and maintenance costs are assumed to be similar to a PWR and fuel costs are assumed to be 54% of a PWR's fuel costs. Based on these assumptions, the economic dispatchability ratio for fast reactor technology has been calculated to be between 57.5-85.8%. These figures suggest that fast reactors of this type are less suitable to load follow economically than thermal nuclear reactors and coal- and gas-fired reactors, which have lower economic dispatchability ratios due to their lower capital costs.

The lifetime of uranium reserves at current extraction rates is estimated at approximately 100 years (IAEA, 2012a). The use of breeder reactors extends this lifetime significantly, since the reactor can breed fuel after the initial input of plutonium and then only requires small inputs of natural (including uranium-238) or even depleted uranium to sustain the nuclear reaction. This fuel cycle can increase the lifetime of uranium resources by a factor of ~50 (presentation, G. Butler, July 5th, 2010). Therefore, it is possible that (based on a uranium and plutonium fuel cycle – i.e. excluding thorium from this calculation) fast breeder reactors could increase the lifetime of fuel resources to around 5 000 years, with the potential of prolonging this lifetime if thorium is also used in FBRs (presentation, G. Butler, July 5th, 2010).

7.2.4.1.2 Technological lock-in

The technological lock-in score calculated for fast breeder reactors is based on its perceived energy flexibility to changing needs in the future, such as the ability to provide heating and cooling in addition to electricity, capability to produce net negative CO_2

emissions, and its ability to produce hydrogen from thermo-chemical processes. Fast breeder reactors are capable of producing two out of three of the future energy requirements specified: tri-generation and hydrogen via thermo-chemical reactions. Therefore, on this ordinal scale fast breeders score a maximum of 20 out of 30. The additional measure – lifetime of the power plant is taken to be 45 years for fast breeder reactors. The overall technological lock-in score for FBRs is then calculated to be 8.9. This score is the same as that calculated for coal-fired power stations, but lower than for CCS power (which scores 20 on this scale).

7.2.4.1.3 Immediacy

The overall time taken from construction to power plant operation for FBRs is estimated to be between 5.5 years (NEEDS, 2008 Oct). This assumption is one that is based on no delays from political opposition, referenda and/or safety and environmental regulations, which, in reality often mean that significant delays are incurred in nuclear projects. This is especially the case in nuclear power plant construction as there is a significant public and political opposition to this form of power generation in the UK. This construction time delay threat is exacerbated for fast breeder reactors as safety, environmental and proliferation concerns are expected to be greater due to the unfamiliarity of the technology. Therefore, the estimate of 5.5 years from time of planning consent to operation is likely to be a conservative one. France’s Superphénix reactor took nine years to construct and achieved criticality in September 1985 (IAEA, 2012b). It is difficult to predict total construction time for fast breeder projects and also thermal reactor projects – delays are encountered for a number of reasons which can cover technical setbacks, economic problems or uncertainty (for example, a drop in uranium price could make a planned fast reactor programme economically infeasible), environmental site issues and general environmental concerns, such as the potential for leaks from fast reactors. To a certain extent, these factors may be planned and accounted for prior to construction. However, in the case of social factors and public opinion on and support for nuclear power, it is much harder to predict and control or influence public opposition to specific nuclear power programmes. Public education, transparency of information (which was not practiced in France in the case of the Superphénix reactor) and inclusion in the decision-making process all go some way to positively influencing public opinion, although it is likely that unfamiliarity with fast reactors and their history of poor reliability, leaks and accidents have a high potential to negatively influence public opinion on such programmes.

7.2.4.1.4 Levelised cost of generation

Finding data on the costs of fast breeder reactors relevant to EFR development in the UK is a hard task as the only commercial reactor in the UK was the Dounreay Fast Reactor which came into operation in 1959, and therefore costs from this period are not relevant to the present costs. Instead, the method of estimation for fast reactor costs has been adopted from NEEDS (2008). This methodology uses current pressurised water reactor (PWR) costs and applies factors to several of the life cycle stages in order to reflect what the potential costs would be for an EFR by taking into account lower fuel costs and higher construction costs. The PWR data that used to estimate the EFR costs are from the IEA's projection of costs for electricity-generating technologies (IEA and NEA, 2010). Cost data on OECD countries have been used for these purposes; there is little information specific to the UK for PWR costs. Therefore, a range of costs across OECD countries is used to obtain potential ranges of EFR costs for the UK (with the NEEDS factors applied to the PWR data). At a discount rate of 5%, the IEA PWR data modified to reflect EFR total levelised costs are between 3.8 – 6.2 pence/kWh. At a 10% discount rate, this rises to a range from 6.7 – 11.3 pence/kWh. The average levelised costs at the 5% and 10% discount rates for the EFR are displayed in Figure 7.33.

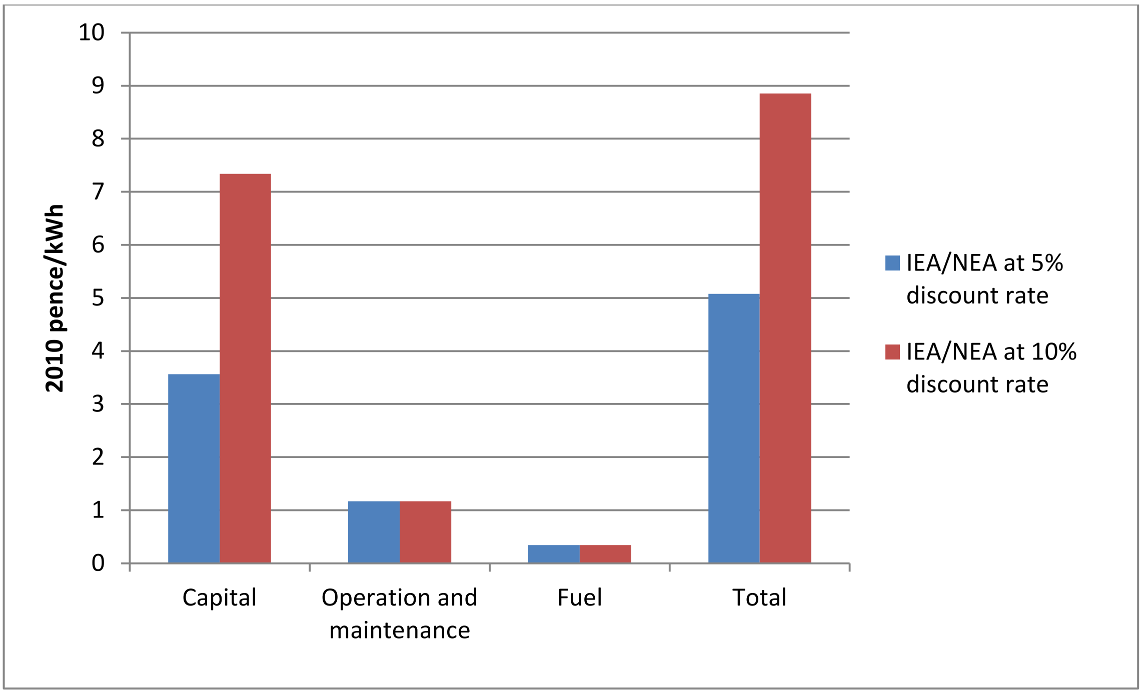


Figure 7.33. Levelised cost estimates for the EFR operating within the UK at 5% and 10% discount rates (IEA and NEA, 2010).

7.2.4.1.5 Cost variability

Using the IEA data modified to reflect EFR costs (at the 10% discount rate), the cost variability ratio for the EFR is 0.04. This is a very low ratio suggesting that fuel costs for the EFR have little impact on the total levelised cost and will therefore not cause large costs fluctuations in consumer electricity prices. The very low contribution of fuel costs to total levelised cost is due to recycling of spent fuel from thermal nuclear reactors which are then able to 'breed' fuel, meaning that the fuel cost along the fuel cycle from the front end of the life cycle are reduced dramatically for fast reactors.

7.2.4.1.6 Financial Incentives

The financial incentives indicator for a particular method of electricity generation is a measure of subsidies across the whole life cycle of a technology. Currently, for fast breeder reactors, there are no policies in place which aim to manipulate the electricity market in order to aid investment in this technology. However, the EU Emissions Trading Scheme would grant an incentive (from 2013) for generation from nuclear sources at a rate of 0.51 p/kWh.

7.2.4.2 Environmental sustainability

The results of the environmental sustainability assessment are discussed under the following headings of the environmental sustainability issues: material recyclability; water eco-toxicity; global warming potential (GWP); ozone layer depletion potential; acidification potential (AP); eutrophication potential (EP); photochemical smog creation potential; and land use and quality. Prior to this, an overview of the goal and scope of the LCA for a fast breeder reactor and a description of the system to be modelled, assumptions and data will be given.

7.2.4.2.1 Goal and scope of the Life Cycle Assessment

The goal of this LCA is to estimate the life cycle environmental impacts of electricity-generation from a Fast Breeder Reactor and compare them to other potential future electricity-generating technologies. The functional unit is defined as 'generation of 1 kWh of electricity'. The scope of the study is from 'cradle to grave'. The following life cycle stages are included within this study: extraction of fuel (uranium and plutonium) and raw materials, processing and transportation of fuel (uranium and plutonium); manufacture and construction of power plant and associated infrastructure; operation of power plant to generate electricity; decommissioning of power plant; and waste disposal. The life cycle of a fast breeder reactor is given in Figure 7.34.

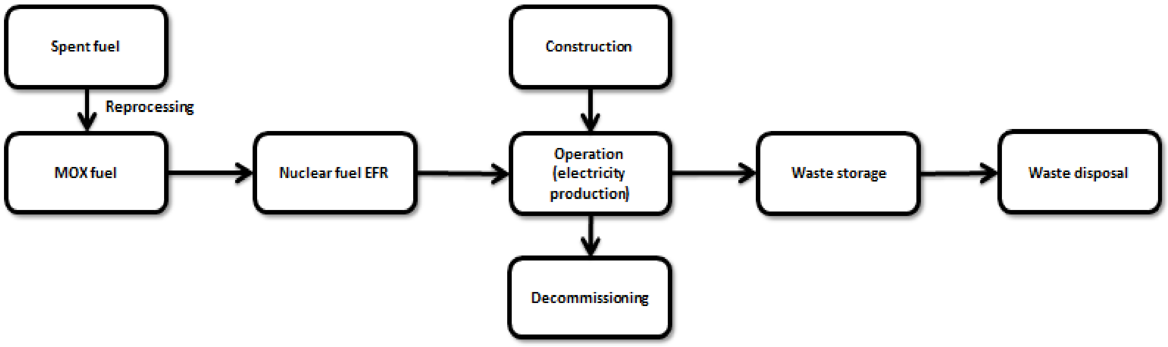


Figure 7.34. Block diagram showing life cycle stages considered in the sustainability assessment of the European Fast Reactor.

7.2.4.2.2 System description and data

For the purposes of this work, one LCI dataset of an EFR from NEEDS has been used in order to compare the likely environmental life cycle impacts of a Generation IV nuclear power reactor to current nuclear reactor innovations and existing technologies (AP1000, EPR and PWR). The dataset is for the reference year 2025 and has been modelled based on the pessimistic, or business as usual (BAU), development for fast reactor technology. This dataset has been chosen based on the current research and development into FBRs as NEEDS acknowledge that their very optimistic scenario is unlikely to occur (NEEDS, 2007).

The specific technology data used for this LCA is a sodium-cooled Fast Breeder Reactor (pool-type), with capacity of 1450 MW, using a plutonium recycling fuel cycle (closed fuel cycle) over 40 years. The LCI data for the Fast Breeder Reactor have been sourced from NEEDS (2008). Specific LCI data broken down into life cycle stages for the EFR model are not available for download from the NEEDS LCI database. The database provides total life cycle information on flow data to and from nature. This data can be accessed from the NEEDS LCI database (NEEDS, 2008).

The NEEDS data on the life cycle of a FBR have been developed based on the information from EDF experts involved in the French Superphenix European Fast Reactor (EFR) power plant. The data provided to NEEDS by EDF included original data for construction and operation of the fast reactor power plant, although data were not available for the disposal stage of the life cycle. To estimate consumption of materials and energy for the disposal stage of the EFR life cycle, the NEEDS inventory for PWR was used (NEEDS, 2007), with a ratio of 1.5 x PWR materials and energy applied for modelling of the EFR. NEEDS (2007) justify this by employing the ratio of concrete use in the original Superphenix reactor to a PWR. The fuel was modelled as ‘mixed oxide fuel element for EFR’, which is a mixture of depleted uranium (from operation of thermal reactors) and recycled plutonium.

The next section presents the Life Cycle Impact Analysis (LCIA) of the FBR under the BAU 2025 scenario specified. The results are compared to a generic PWR modelled specific to European conditions (EcoInvent, 2010) for comparison.

7.2.4.2.3 Impact assessment and interpretation of the results

The life-cycle environmental impacts presented below have been calculated using the CML 2001 methodology (CML, 2002), with the exception of the material recyclability indicator and one aspect of the land use and quality issue. The life cycle impact data for the EFR can only be presented as total life cycle impacts for each environmental indicator as NEEDS do not provide the LCIA data broken down by life cycle stage.

The life cycle environmental impacts of the European fast Reactor and a generic European PWR are displayed in Figure 7.35. As shown in the graph, the European fast Reactor (EFR) has the lowest environmental impact for every indicator when compared to a generic European PWR. On average, the impacts from the PWR are 300 times higher than the impacts of the EFR. The biggest increase is for the ozone depletion potential, which is 2 000 larger for the PWR compared to the EFR. The smallest increase is for the terrestrial eco-toxicity, which is 132% higher for the PWR compared to the EFR. Although it is not possible to determine where the contributions for each life cycle impact originate from over the life cycle of the EFR (as the data used from NEEDS have been aggregated over the whole life cycle the contributions to environmental impacts from the European PWR are assessed below in order to determine what factors cause increases in these potential impacts.

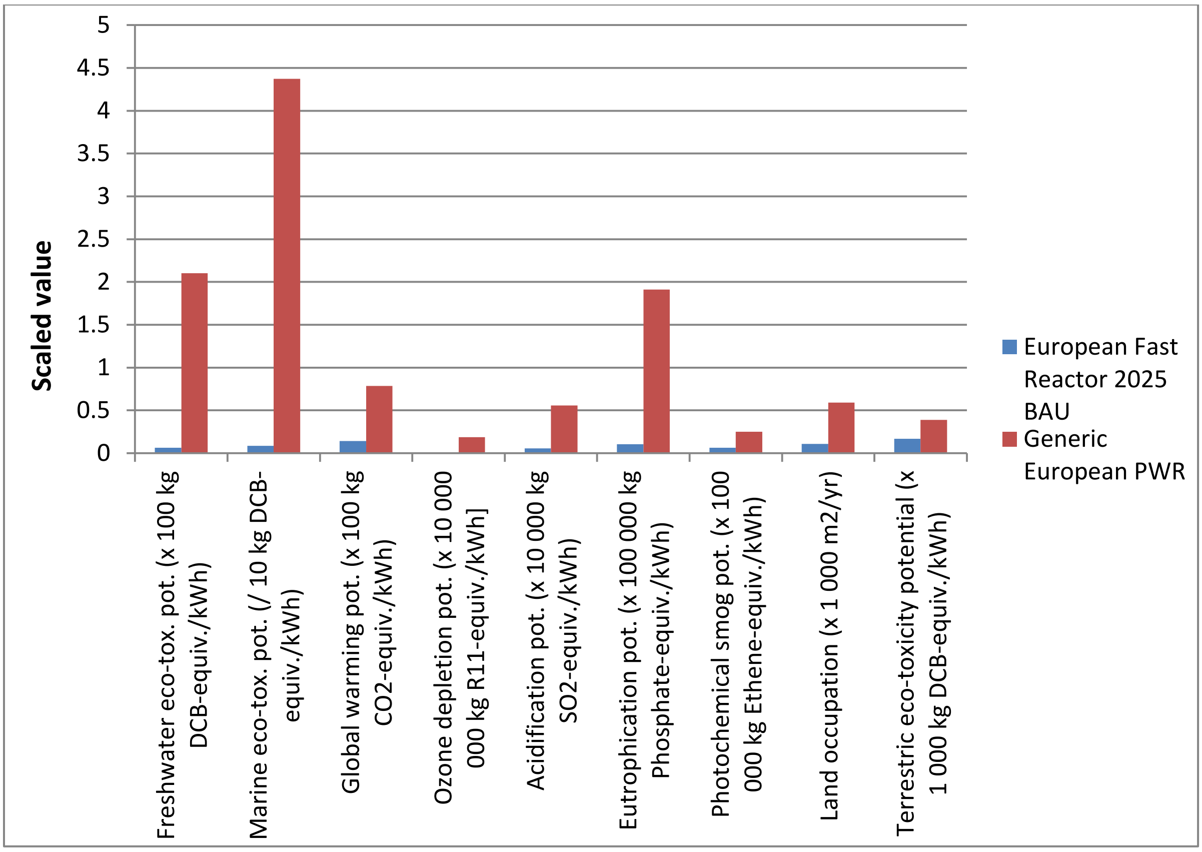


Figure 7.35. Life cycle environmental impacts of the European Fast Reactor and a generic European Pressurised Water Reactor. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.4.2.4 Material recyclability

The extent to which a power plant can be recycled after decommissioning and dismantling is governed by the materials used in construction of the power plant and whether the recyclable materials have become contaminated to such an extent that they are considered hazardous. The potential for contamination is much greater in nuclear power plants due to the radioactive fuel used. When compared to thermal reactors, fast reactors exhibit greater recycling potential as they have the ability to burn long-lived actinides which would otherwise exist in thermal reactors.

As the data for the EFR have been sourced from NEEDS and are in such a format (aggregated life cycle inventory) that does not allow materials used in the construction of the power plant to be viewed, a proxy for the amounts of various materials has been used in order to estimate the recyclability of the EFR upon decommissioning. The NEEDS report on the EFR states that building materials for a sodium-cooled fast reactor would be around one and a half times those of a typical PWR. Therefore, recyclability of the input building materials for the EFR are considered to be similar as for a PWR. When averaged by weight of the main components of the power plant that are recyclable, the total recyclability of the fast reactor is 81.3%.

7.2.4.2.5 Water eco-toxicity

Water eco-toxicity includes the freshwater eco-toxicity and marine eco-toxicity indicators and is measured in kg of 1,4-dichlorobenzene equivalents. The freshwater eco-toxicity potential for the EFR is 6.5 x 10^{-4} kg DCB-equivalent/kWh, which is 3.1% of that for a generic European PWR (2.1 x 10^{-2} kg DCB-equivalent/kWh). By looking at the life cycle stage contributions to the freshwater eco-toxicity for the PWR, it can be observed that the much higher impact from the life cycle of the PWR compare to the EFR is from the uranium milling and construction life cycle stages. As fuel is created in fast breeder reactors, most of the front end of the life cycle (which includes mining, milling, conversion and enrichment) is not carried out in order to provide fuel for FBRs. Similarly, the majority (76.5%) of the marine eco-toxicity result for the PWR is attributed to uranium milling, followed by construction of the PWR (7.5%).

7.2.4.2.6 Global warming potential

The global warming potential for the EFR is estimated at 1.4 g CO_2 equiv./kWh, compared to 6.8 for the European PWR. The life cycle break-down results for the European PWR show that around a third of the GHG emissions come from the construction of the power plant, 22% from milling, and 19% from the conversion stages. As the front end of the life cycle of the EFR does not include that majority of the impacts from mining and processing of uranium into fuel, it can be assumed that the GWP impact for the EFR must come from construction of the fast breeder reactor, in addition to decommissioning of the power plant and radioactive waste storage.

7.2.4.2.7 Ozone layer depletion potential

The ozone depletion potential for the PWR is 1.89 x 10^{-8} kg R11-equivalent/kWh, which is around 200 times greater than the result for the EFR (9.03 x 10^{-11}). The ODP figure for the

European PWR is attributed mostly to uranium conversion (28%) and milling (27%). As uranium conversion and milling are not included in the EFR life cycle, the ODP value is mostly attributable to the construction of the fast reactor, which has the next highest impact for ODP.

7.2.4.2.8 Acidification potential

The acidification potential (AP) for the European PWR is around ten times greater (5.58×10^{-5} kg SO_2-equivalent/kWh) than for the EFR (5.5×10^{-6} kg SO_2-equivalent/kWh). The main contribution of the PWR figure comes from the milling stage of the life cycle (44%), followed by construction (18%) and mining (15%). Therefore, it is likely that the AP of the EFR is attributed to the construction of the power plant as milling and mining are not carried out in the EFR life cycle.

7.2.4.2.9 Eutrophication potential

The eutrophication potential for the European PWR (1.91×10^{-5} kg phosphate-equivalent/kWh) is 18 times greater than the EP of the EFR (1.04×10^{-6}). Again, the main contributors for EP are milling (37%), construction (24%) and mining (11.5%), implying that the EP for the EFR is attributable to the construction stage of its life cycle.

7.2.4.2.10 Photochemical smog creation potential

The photochemical smog creation potential result for the European PWR is 2.51×10^{-6} kg ethene-equivalent/kWh, which is 3.9 times higher than the result for the EFR (6.48×10^{-7}). The main contributor to the life cycle for the PWR is milling (40%), followed by construction (22%) and conversion (15.5%). Again, the result for the EFR must be mostly attributed to the construction stage of its life cycle, given that the front end of the fuel cycle is not needed for fast reactors.

7.2.4.2.11 Land use and quality

The land occupation (m^2 multiplied by years occupied) is 1.1×10^{-4} for the EFR and 5.9×10^{-4} for the PWR. Land occupation for the PWR is attributed mostly to the power plant construction (54%), then to milling (21%). Land occupation for the EFR is minimised due to the absence of the mining, milling, conversions, enrichment and fuel fabrication life cycle stages from operation of the EFR.

As there are currently no plans to build fast reactors in the UK, it is impossible to place a concrete figure on the greenfield land use indicator. However, due to land constraints in the UK and the need for nuclear power plants to be developed away from built-up areas, it is likely that any new fast reactors would be built on greenfield land.

The terrestrial eco-toxicity potential for the EFR stands at around 1.68 g DCB-equiv./kWh. For a European PWR, this figure is 3.9 g DCB-equiv./kWh, which is 132% higher than the EFR figure. Terrestrial eco-toxicity potential from the PWR is attributed mainly to the milling stage of the life cycle (89.5%) and the effect the uranium tailings have on land. The next biggest contributor to this indicator is construction of the power plant, and this is where the source of the toxic emissions to land from the EFR must therefore originate.

7.2.4.3 Social sustainability

The results of the social sustainability assessment are discussed below under the following headings of the social sustainability issues: provision of employment; human health impacts; large accident risk; local community impacts; human rights and corruption; energy security; nuclear proliferation; and intergenerational equity.

7.2.4.3.1 Provision of employment

Due to a lack of reliable data on the employment that a fast reactor would create both directly and indirectly, again, data for the employment of a pressurised water reactor have been used (Stamford and Azapagic, 2012). Although some aspects of the values used will be overestimations (i.e. mining employment and fuel processing would be a fraction of those of for a PWR), construction of a fast reactor would invariably be more complex and more materials and time would be needed. Nevertheless, direct employment and total employment values of 56 person-years/TWh and 81 person-years/TWh respectively are assumed for the fast reactor.

7.2.4.3.2 Human health impacts

Worker fatalities

A worker injury rate of 0.6 injuries/TWh has been assumed, taking the data for the worker fatalities from Stamford and Azapagic (2012). Related to employment, again, this figure is likely to be an overestimate of those injuries attributed to the mining and front-end fuel cycle, but those attributed to construction and decommissioning are likely to be an underestimate.

Human toxicity potential and human health impacts from radiation

Over the whole life cycle, the generic European PWR has a human toxicity potential that is 2172% higher than the HTP for the EFR (per kWh the PWR life cycle has a HTP of 0.11 kg DCB-equivalent and the EFR has a HTP of 0.005 kg DCB-equivalent per kWh), as displayed in Figure 7.36. Human health impacts from radiation total 2.57 x 10^{-8} DALY per kWh for the PWR and 2.55 x 10^{-9} DALY per kWh for the EFR over the whole life cycle, meaning that the PWR's impacts for this indicator are 908% greater than the ERF's.

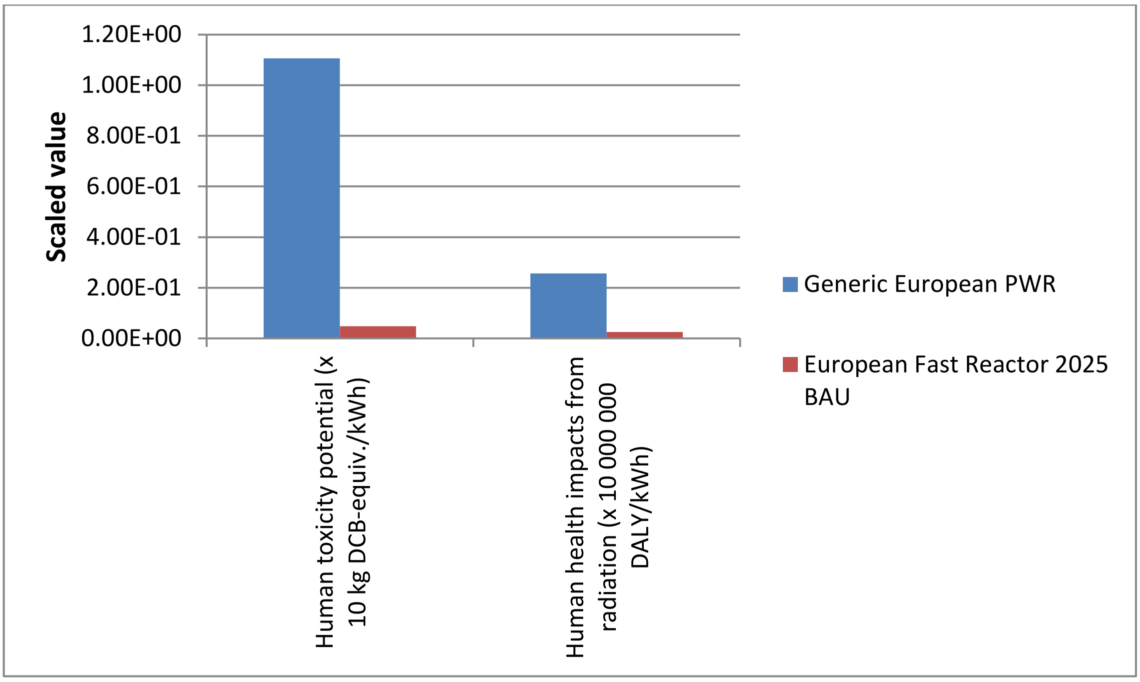


Figure 7.36. Human toxicity potential (HTP) and human health impacts from radiation life cycle impacts of a generic European PWR and a European fast reactor. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.4.3.3 Large accident risk

A reliable assessment for a FBR cannot be made due to the lack of risk assessment of these types of reactors and because data on accidents of FBRs are hard to estimate from past operation as very few have been in operation compared to thermal nuclear power plants, globally. Therefore, the estimate of fatalities due to large accidents is again taken for PWR from Stamford and Azapagic (2012). A value of 1.22 x 10^{-3} fatalities/PWh has been assumed.

7.2.4.3.4 Local community impacts

The indicators determined for local community impacts have not been calculated for this assessment as this is a company-specific indicator.

7.2.4.3.5 Human rights and corruption

The calculation of human rights and corruption impacts calculated for a fast reactor fuel cycle operating within the UK is a less straightforward task than the calculations carried out for the other three technologies assessed in this work. Drawing a boundary around a fast reactor life cycle is particularly difficult – uranium from a variety of countries is sourced for use in thermal nuclear reactors and the waste, or spent fuel from operation of the thermal reactors may then be used as fuel in fast breeder reactors. Cutting out the whole front-end of the fuel cycle (as it is not directly relevant to fast breeder reactors) from the life cycle of FBRs would mean that the only country that would be considered within the corruption index would be the UK (as reprocessing of the fuel is carried out in the UK). Another argument to take this perspective is that spent fuel would have to be treated as long-lived radioactive waste if it was not used in FBRs and the operation of UK thermal reactors has been carried out with the intention of disposing of, rather than recycling spent fuel. Taking this perspective, an average Corruption Perceptions Index of 7.8 is determined for fast breeder reactors (Transparency International, 2011).

7.2.4.3.6 Energy security

Amount of fossil fuel potentially avoided

Stamford and Azapagic (2012) determined that 1 kWh of electricity from the UK's current fossil fuel fleet would require 0.2 kg of oil equivalent. This value is the same for the PWR as the same amount of fossil fuel is avoided through the use of any type of nuclear fuel.

Diversity of fuel supply

The diversity of the UK's spent nuclear fuel supply for reprocessing and using in FBRs is calculated via the Simpson's Index of Diversity (SID) (Stamford and Azapagic, 2011), The calculated SID is then used to determine the diversity of fuel supply (DFS) through multiplication this value by the proportion of fuel supplied from imports, added to the supply of fuel that is provided indigenously. The overall DFS for reprocessed nuclear fuel in the UK would be 1, as spent fuel is produced and reprocessed indigenously (with a score of 1 representing a diverse fully supply and a score of 0 representing a fuel supply that is overly reliant on one nation for its supplies).

Fuel storage capability

This indicator is expressed in terms of energy content of the fuel per unit mass of fuel stored. This indicates fuel storage needs for different types of fuels. The energy density of uranium fuel for thermal reactors has been calculated to be 10 million GJ/m^3, assuming a burn-up of 50 GW d/tU (Stamford and Azapagic, 2011). Given that reprocessing fuel can give ~50 times the energy from the same amount of mined uranium as thermal reactors (including the PWR), the energy density for fast breeder reactors therefore increases to around 500 million GJ/m^3 (with the value for the PWR being around 10 million GJ/m^3).

7.2.4.3.7 Nuclear proliferation

The measure of nuclear proliferation of nuclear technologies is measured using three components to this indicator: use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; and requirement for enriched uranium. Nuclear proliferation is defined as the use nuclear weapons or the spread of weapons technology and therefore the measures proposed seek to identify technologies that are particularly at risk of proliferation. The first criterion addresses the ease at which weapons usable spent fuel may be extracted from nuclear reactors. Sodium-cooled fast reactors are not capable of online refuelling due to the necessary shut down of the reactor and extraction of the liquid sodium from the pressure vessel. Enriched uranium is also not needed to produce fuel for the fast reactor fuel cycle (although it could be argued that enrichment facilities are indirectly linked to the FBR fuel cycle as spent fuel from thermal reactors is used in MOX fuel for FBRs). Reprocessing is needed in order to produce the MOX fuel, but enriched uranium is not needed by fast reactors in order to produce electricity. Therefore, FBRs score 1 out of a maximum 3 for nuclear proliferation potential using the above measures.

7.2.4.3.8 Intergenerational equity

Use of elemental and abiotic resources

Figure 7.37 displays the life cycle impacts of the use of abiotic elemental resources and fossil fuel resources for the generic European PWR and the FBR. Use of abiotic elemental resources totals 5.41 x 10^{-5} kg Sb-equivalent per kWh for the generic European PWR and 1.64 x 10^{-8} kg Sb-equivalent per kWh for the EFR over the whole life cycle. Therefore, generic European PWR depletes around 3 000 times more abiotic resources than the EFR.

Use of fossil fuel resources totals 0.1 MJ/kWh for the European PWR and 0.02 MJ per kWh for the EFR over the whole life cycle.

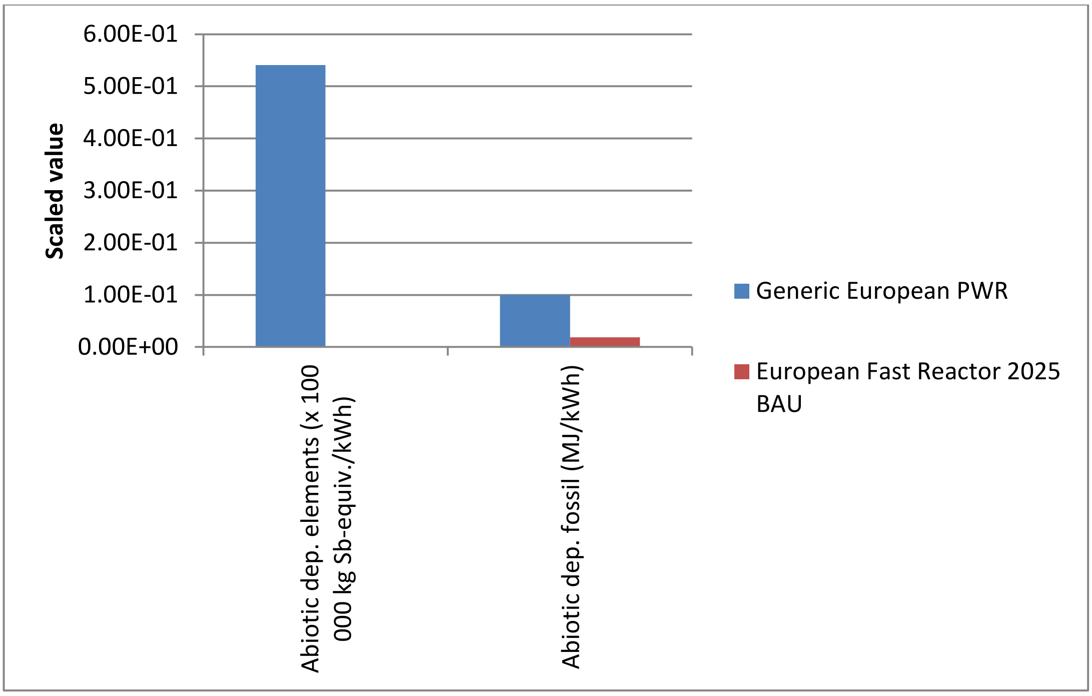


Figure 7.37. Full life cycle impact of a generic European PWR and a FBR for the depletion of abiotic resources and depletion of fossil fuel resources indicators. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Radioactive waste to be stored

Although fast reactor can use up 1% of plutonium in spent fuel from thermal reactors as fuel, and the majority of the rest of spent fuel as make-up feed, spent fuel waste from thermal reactors is relatively small compared to additional high level and intermediate level waste. Furthermore, no accurate estimates of the amount of radioactive waste produced by FBRs could be found. A value of 1.2 m^3/TWh has been assumed (Stamford, 2012).

7.2.5 Assessment of the sustainability of coal-fired power with post-combustion carbon capture and storage

7.2.5.1 Techno-economic sustainability

The results of the techno-economic sustainability assessment are discussed under the following headings of the techno-economic issues: operability; technological lock-in; immediacy; levelised cost of generation; cost variability; and financial incentives.

7.2.5.1.1 Operability

The capacity factor for post-combustion coal CCS is assumed to be around 83% from several case studies (IEA, 2011b). This is higher than capacity factors published for conventional coal-fired power. For example, the Drax coal-fired power station in Yorkshire, UK, has an average capacity factor of 71% over an eight year period (2000-2008), although the capacity factor became larger towards the end of this period, starting at 67% in 2000 and rising to 78.5% in 2008 (Stamford, 2012). However, it may be likely that coal CCS power will exhibit higher capacity factors than conventional coal power stations as it would make sense for them to be run at a higher load for a higher proportion of time due to the higher capital costs associated with coal CCS power. It should also be noted that the full chain of the coal CCS is not currently in operation at a commercial scale and therefore the figures suggested for its capacity factor may be inaccurate.

Very little information is available on the availability factor of future commercially operated post-combustion coal CCS power plants. In this case, the availability factor of a pulverised coal-fired power station is used as a proxy. This availability factor has been calculated to be 90.7% (Stamford and Azapagic, 2012). Down-time of power plants is associated with re-fuelling (in the case of nuclear power), maintenance, and in the case of renewable technologies, adverse weather conditions and/or insufficient primary input energy. In the case of coal-fired power and coal CCS power, down-time of the power plant is associated with maintenance. As the coal CCS power station is larger and is a more complex operation than conventional coal-fired power, it could potentially lead to less availability of the power plant if more time is needed to maintain these complex systems.

Again, there is not much data on these measures for coal CCS. However, DECC have published a report on the Kingsnorth carbon capture and storage project (DECC, 2011) which has identified in simulations a potential ramp-up and ramp-down rate of 10.7% *P* max per minute. CCS power plants are not yet being run on a commercial scale, therefore obtaining data on the minimum up and down times is also very difficult. Cohen *et al.* (2012) state that although there is limited understanding of the technical characteristics of large-scale coal-fired CCS power stations, the operating ranges of the CO_2 capture unit should not affect the ramp up and down rates of coal-fired power stations with carbon capture units. Therefore, the minimum up- and down-times for coal CCS have been assumed to be the same, or broadly similar to a pulverised coal-fired power station.

However, with regard to minimum up and down times of coal CCS power stations, the minimum downtime may be increased due to unforeseen technical running issues with the carbon capture unit. Failure of the carbon capture equipment is a possibility as operation of the equipment on a large, commercial scale has not yet been carried out. In addition, as coal-fired power stations are currently used within the UK electricity mix to add to base load generation (after nuclear power) and also at certain times to respond to peak demand, coal-fired carbon capture power stations will be expected to be operational for long periods of time, with minimised down-time in order to replace the generating capacity and technical capability of traditional coal-fired power stations. This could also add to potential equipment or system failures if the capture unit is put under stress of long operational times. Theoretically, the minimum down-time of a coal-fired power station with a CCS capture unit should lie somewhere around 300 minutes (GREA, 2010) with the possibility of this increasing depending on the reliability of the carbon capture unit.

The ratio of capital cost to total levelised cost for post-combustion coal CCS has been determined by using the cost data from Mott Mac Donald (2010) – see section on levelised costs below. The economic dispatchability ratio for this technology has been calculated to be 55%. This is a higher ratio than for gas-fired and coal power, which are usually used to follow load. The CCS power plant has higher capital costs due to higher construction and infrastructure costs as it has additional life cycle stages compared to gas- and coal-fired power. This means that it is not as suitable to be economically dispatchable as traditional fossil fuel technologies, although it is more suitable under this measure than nuclear power, which has an economic dispatchability of around 70% (Stamford and Azapagic, 2011).

The current lifetime of coal reserves at current extraction rates is 118 years (WCI, 2012). As the use of carbon capture within coal-fired power stations imposes an energy penalty of 10.2% (IPCC, 2005), the lifetime of coal reserves drops to 107 years for coal carbon capture and storage technologies.

7.2.5.1.2 Technological lock-in

Coal CCS scores well on the flexibility of energy generation measures. Coal CCS power stations can provide heating, cooling and electricity (tri-generation), can produce hydrogen via thermal/thermochemical processes and would potentially be able to generate electricity with negative carbon emissions if proportionally enough biomass was used in addition to coal to result in net negative emissions. Therefore, coal CCS scores on all measures on the ordinal scale on this aspect of the technological indicator with a score of 30 out of 30 (the maximum being 30 – a score of 10 for every criterion met). This score is then squared in order to reduce this indicator's sensitivity to the lifespan of the power plant. On average, coal-fired power stations have a lifetime of 45 years and it is expected that coal CCS power stations will operate for the same number of years. Therefore, the overall score for coal CCS is 20 ($30^2/45$). In contrast, the score for coal-fired power is 8.9 on the technological lock-in scale (coal scores 20 out of 30 for the technology flexibility measures, but has the same lifetime as coal CCS).

7.2.5.1.3 Immediacy

The overall time taken from construction to power plant operation is expected to be 4-5 years (DECC, 2012c). The complicating factor in construction times for CCS is that many coal-fired power stations can be retrofitted, which would obviously take much less time than building a power plant complete with CCS capability from scratch. However, for purposes of consistency and comparison to other electricity-generating options, the length of time taken into account for immediacy for coal CCS will be the full construction time of the whole power plant.

7.2.5.1.4 Levelised cost of generation see CCS paper

A study by Parsons Brinkerhoff on the costs of power in the UK found that the total levelised cost of coal with post-combustion CCS was between 10 – 15.5 pence/kWh power generated at a 10% discount rate (Parsons Brinkerhoff, 2010). Mott MacDonald published total levelised costs of 13.6 pence/kWh for UK-based coal-fired power station with post-combustion CCS (Mott MacDonald, 2010). The breakdown of the life cycle costs for coal power with post-combustion capture CCS are displayed in Figure 7.38 at a 10% discount rate. The life cycle costs of the remaining three technologies in this chapter have been derived from the IEA and NEA's Projected Costs of Generating Electricity. However, the CCS costs stated in this report do not include estimates for the costs of storage, and therefore cannot be used in order to obtain estimates of the cost of the full CCS life cycle chain.

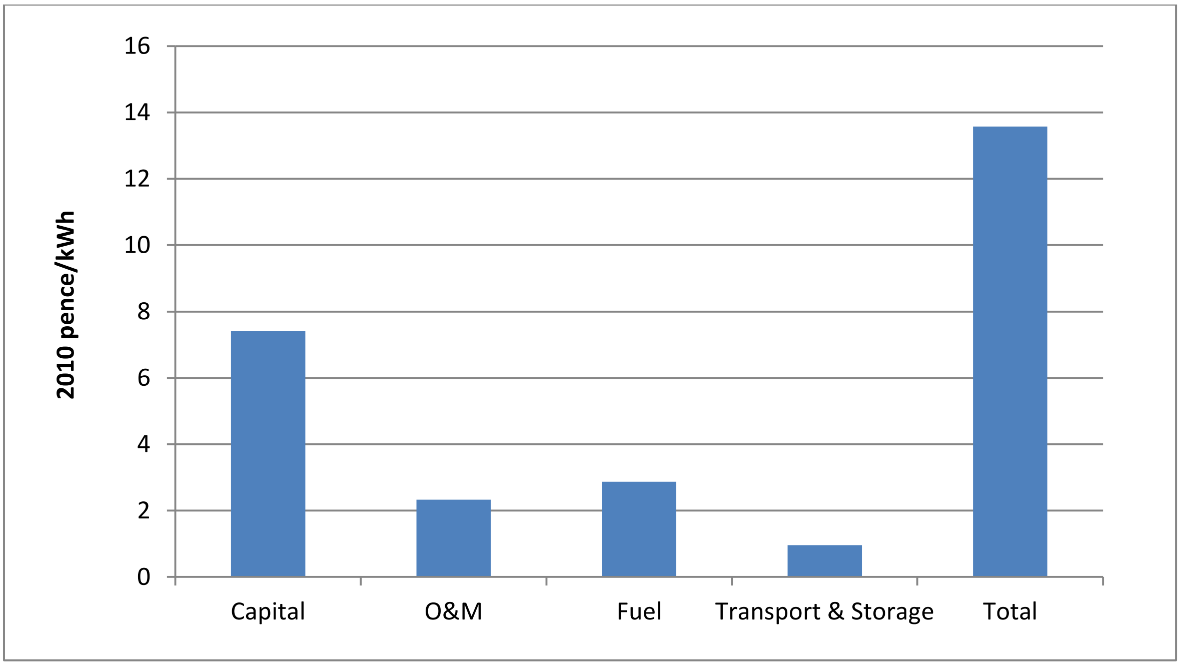


Figure 7.38. Levelised cost estimate for coal-fired power with post-combustion CCS operating within the UK at a 10% discount rate (Mott MacDonald, 2010).

7.2.5.1.5 Cost variability

Using the Mott MacDonald data for post-combustion coal CCS, the cost variability ratio is 0.21. This ratio is relatively low compared to coal-fired power (0.35) and the ratio for gas-fired power (0.74) (Stamford and Azapagic, 2011). This is because the fuel costs are low when taking into account the total extra costs of coal CCS (due to the transport, storage and extra capital costs to build the capture, transport and storage infrastructure). Therefore, compared to coal- and gas-fired power, post-combustion coal CCS has a lower cost variability.

7.2.5.1.6 Financial Incentives

In relation to the development of CCS technologies, specific policy instruments that are currently being used to commercialise this technology include: direct invest into companies developing CCS technologies; HSE work on site selection studies for CO_2 injection and storage; and Contracts for Difference (CfD). The total funding allocated to

CCS technologies by the government at the current time is valued at £1 billion, with additional support from CfD, subject to affordability (DECC, 2012b). The £1 billion investment is aimed to support CCS projects in their infancy, in the hope that by the 2020s, reform of the electricity market and CCS technology development will mean that this technology will be economically viable in the market without public funding. Determining the extent of public funding allocated for development and eventual large-scale deployment of CCS technologies is complicated by the fact that the investment proposed by the government is to be over a limited time period of around 15 years in order to remove barriers to private investment in CCS and to develop the technology sufficiently for investment risks to be lowered. Therefore, the investment of £1 will be a finite subsidy for CCS, and it is hoped that it will lead to large-scale deployment of the technology from 2030 onwards. Therefore, allocation of this funding to the technology on a per kWh electricity generated basis is especially difficult as this technology is new and not currently operating in the UK.

CCS technologies will also benefit from the carbon price under the EU Emissions Trading Scheme, which will be introduced in 2013 with a price of £16/tCO_2. For CCS power plants with a 90% capture rate for carbon, the carbon price subsidy would be granted at a rate of 0.46 p/kWh.

7.2.5.2 Environmental sustainability

The results of the environmental sustainability assessment are discussed under the following headings of the environmental sustainability issues: material recyclability; water eco-toxicity; global warming potential (GWP); ozone layer depletion potential; acidification potential (AP); eutrophication potential (EP); photochemical smog creation potential; and land use and quality. Prior to this, an overview of the goal and scope of the LCA for the post-combustion CCS coal-fired power station and a description of the system to be modelled, assumptions and data will be given.

7.2.5.2.1 Goal and scope of the Life Cycle Assessment

The goal of this life cycle assessment is to estimate the life cycle environmental impacts of electricity-generation from a post-combustion coal-fired CCS power plant operating in the

UK and compare them to selective nuclear technologies. The functional unit is described as 'generation of 1 kWh of electricity'. The scope of the study is from 'cradle to grave'. The following life cycle stages are included within this study: extraction of fuel (coal) and raw materials, processing and transportation of fuel (coal); manufacture and construction of power plant and associated infrastructure; operation of power plant to generate electricity; decommissioning of power plant; and waste disposal. The life cycle of a post-combustion carbon capture coal-fired power plant is displayed in figure Figure 7.39.

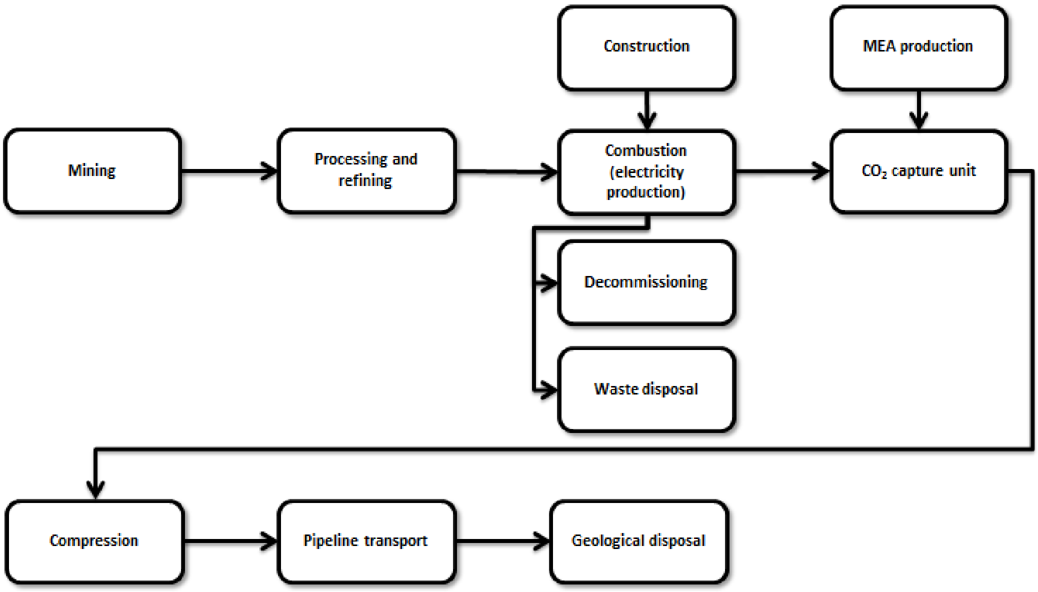


Figure 7.39. Block diagram showing life cycle stages considered in the sustainability assessment of coal-fired power with CO_2 capture, transport and storage.

7.2.5.2.2 System description, assumptions and data

The specific technology modelled for this life cycle assessment is a pulverised coal (hard coal) power plant of 500 MW capacity, with a capacity factor of 62%. and a 45 year lifetime. The plant is assumed to be operated in the UK and the data have been adapted to reflect UK conditions where possible. The data for modelling of the pulverised coal power plant are taken from the EcoInvent database (EcoInvent, 2010). This plant has been modelled with and without carbon capture capability in order to compare a coal-fired power plant of the same technology to one which has had the additional carbon capture, transport and storage processes added to it. The obtained results have been compared to the life cycle impacts of the coal-fired power stations with and without CCS obtained by the

NEEDS Project (NEEDS, 2008). Modelling of the full CCS life cycle includes the carbon capture process, transport along an offshore pipeline and storage in a depleted oil/gas reservoir in the North Sea. These data are not readily available in the EcoInvent database. In order to model the full life cycle of CCS, processes from the EcoInvent database have been adapted to represent the CO_2 capture, transport and storage stages of the CCS life cycle. The assumptions made are described below.

7.2.5.2.3 CO_2 Capture Process

The capture process of the CCS-enabled power station is assumed to reduce CO_2 emissions from combustion by 90%. Although this is an upper limit in reduction of carbon emissions, this work aims to show the LCA impacts of the best case scenario for post-combustion carbon capture. The values for increases in materials needed to build the CO_2 capture infrastructure have been taken from literature (Cormos, 2010). The increase in amounts (compared to coal-fired power stations without CCS) range from an additional 70-75% for concrete and steel types used, 24% for copper and polyethylene and 10% for aluminium. In addition to the materials needed for construction, the CO_2 capture process requires energy for the capture unit to operate and for compression of the CO_2, following removal from the flue gas stream. The ‘energy penalty’ for the capture unit is assumed to be 10.2% extra coal needed for combustion (IPCC, 2005). CO_2 is removed from the flue gas stream using the solvent monoethanolamine (MEA). It is assumed that 1.6 kg of MEA is required per tonne of CO_2 captured from the flue gas stream (IPCC, 2005). In addition to the MEA solvent, caustic soda (1.3×10^{-4} kg per kg CO_2 capture) and activated carbon (6×10^{-5} kg per kg CO_2 capture) are also required for solvent reclamation and to remove degradation products, and cooling water is also needed. These values are also taken from literature (Singh *et al.*, 2011).

7.2.5.2.4 CO_2 Transportation

Transport of the captured CO_2 is assumed to be carried out using the pipeline method. This is the most likely method of transportation for CO_2 captured within the UK due to the proximity of many coal-fired power stations to the North Sea, and the presence of oil and gas industry infrastructure already existing, which will make the task of installing pipelines for CO_2 transport to depleted oil and gas fields in the North Sea easier and less costly. The majority of storage capacity is offshore and this is the preferred Government option. In addition, there is currently no regulatory framework for onshore storage. An offshore gas pipeline of 500 km length used to transport gas from the North Sea has been selected from the EcoInvent database as a proxy for CO_2 transport to the North Sea. The pressure at which natural gas is transported from the North Sea in offshore pipelines is typically between 200-250 bar, which is twice the pressure required for CO_2 transportation (Singh *et al.*, 2011). Although this means that the materials and energy attributed to pipeline transportation are likely to be an over-estimate of the requirements, this conservative estimation is assumed as natural gas transportation is the only available data in the EcoInvent database and CO_2 transport along pipelines at a large, commercial scale has not yet been carried out, therefore the projected pressure of 110 bar for CO_2 may be an inaccurate estimate. A compressor station at the power plant used to compress the CO_2 has also been included in the LCA. The distance of 500 km is selected to reflect the transport distance needed along the pipeline from the UK mainland to many of the North Sea depleted oil and gas reservoirs. The pipeline is assumed to have a lifetime of 40 years. The process for pipeline transport in EcoInvent is modified to reflect the conditions under which CO_2 would be transported. To do this, natural gas production is deleted from this process and the energy requirement for re-pressurisation of the CO_2 is modified. This energy is needed along the pipeline to keep the CO_2 above critical pressure. A value of 0.011 kWh per tkm (tonne-kilometre) is added to the energy requirement for compression along the pipeline (Wildbolz, 2007) and a compressor station is needed at 300 km in order to re-compress the CO_2. In order to attribute the correct proportion of impact of the pipeline's manufacture and transportation along the pipeline during its lifetime, a factor of 6.72×10^{-12} has been applied to every kWh electricity production from the power plant. This factor has been calculated by determining the amount of electricity (in kWh) produced over the power plant's lifetime and dividing the impacts of the transport pipeline by this number. These and additional materials used in the life cycle of post-combustion coal CCS are summarised in Table 7.2.

7.2.5.2.5 CO_2 Storage

Depleted oil and gas reservoir storage has been specified for long-term storage of CO_2 captured from the post-combustion CCS power plant. A reservoir depth of 1000 m has been assumed for storage of the CO_2. This depth is typical of many depleted oil and gas reservoirs in the North Sea. The EcoInvent process ‘well for exploration and production’ has been chosen as a proxy for CO_2 storage in depleted oil and gas reservoirs in the North Sea. This process takes account of the materials and energy required for production of a well for which CO_2 will be pumped into for storage in the reservoir. The materials and energy needed for exploration of oil and gas are assumed to be similar to those needed for CO_2 storage exploration activities. It is estimated that a 500 MW coal-fired power station will produce around 2.5 Mt of CO_2 every year (Blunt, 2010). At a 90% capture rate over an operational lifetime of 40 years, the CO_2 storage reservoir will need to accommodate around 90 MT of CO_2 from a 500 MW power station. A depth of 800 metres is the minimum depth at which CO_2 will remain in the dense phase, storage below this depth will therefore maximise storage capacity (Holloway, 2008). A well depth of 1000 metres has been selected for this study, as a storage reservoir is likely to be selected to be deeper than the minimum recommended depth to provide a margin of safety, yet shallow enough to be economically constructed. The process, ‘well for exploration and production’ has been updated to reflect the materials and energy needed in order to produce a well for CO_2 storage. The inputs ‘natural gas, vented’ and ‘natural gas, sour, burned in production flare’ have been deleted from this process as they are only applicable to production scenarios and would not exist in a CO_2 injection case. In addition to this, extra energy is also needed to compress the CO_2 again before it is injected into the well. Another re-compression station has been added here in order for the CO_2 to be pressurised again before it is injected into the well. The extra energy needed is estimated to be 14.3 kWh per tonne of CO_2 injected (Wildbolz, 2007). It is assumed that over the lifetime of the power plant, 90 Mt of CO_2 will need to be injected into the North Sea. Therefore, 4 633 200 000 MJ of natural gas are needed to compress and inject CO_2 into the reservoir over 45 years of the power plant’s lifetime.

Again, in order to attribute the correct proportion of impacts of the injection well’s materials used and energy consumption for storage, a factor of 6.72×10^{-12} has been applied to every kWh electricity production from the power plant. This factor has been calculated by determining the amount of electricity (in kWh) produced over the power plant’s lifetime and dividing the impacts of the transport pipeline by this number.

The next section presents the Life Cycle Impact Analysis (LCIA) of a post-combustion capture CCS life cycle. The results are compared to a generic pulverised coal-fired power station modelled under UK-specific conditions where data are available.

Table 7.2. Material requirements, fuel use and CO_2 capture for post-combustion coal CCS power.

Material	Per kWh Electricity Produced	Per Power Plant (lifetime of production)
Concrete (m^3)	7.45×10^{-5}	91 052
Chromium steel (kg)	5.67×10^{-4}	693 720
Low-alloyed steel (kg)	5.11×10^{-3}	6 243 559
Reinforcing steel (kg)	5.99×10^{-2}	73 191 700
Copper (kg)	6.58×10^{-4}	805 248
Aluminium (kg)	2.68×10^{-4}	327 777
Polyethylene (kg)	5.07×10^{-4}	619 745
Coal (kg)	0.042	51 359 994
CO_2 captured (kg)	0.9	1 100 571 300
Monoethanolamine (kg)	1.6×10^{-3}	1 956 571

7.2.5.2.6 Impact assessment and interpretation of the results

The life-cycle environmental impacts presented below (Figure 7.40) have been calculated using the CML 2001 methodology (CML, 2002), with the exception of the material recyclability indicator and one aspect of the land use and quality issue.

The life cycle environmental impacts of the CCS coal-fired power station (with post-combustion capture) and a pulverised coal-fired power station are compared in Figure 7.40. As shown in the graph, the CCS has the highest environmental impact than coal power plant for every indicator apart from the global warming potential, on average by 2.3%.The biggest increase is for the ozone depletion potential, which is 17% higher for the for CCS power than coal-fired power. On the other hand, there is a substantial decrease in the global warming potential indicator (-72.5%) for the CCS power station over the whole life cycle. The next sections detail the individual impacts and compares these results to those from a coal-fired power station. The life cycle stages that contribute most to each impact category are also identified.

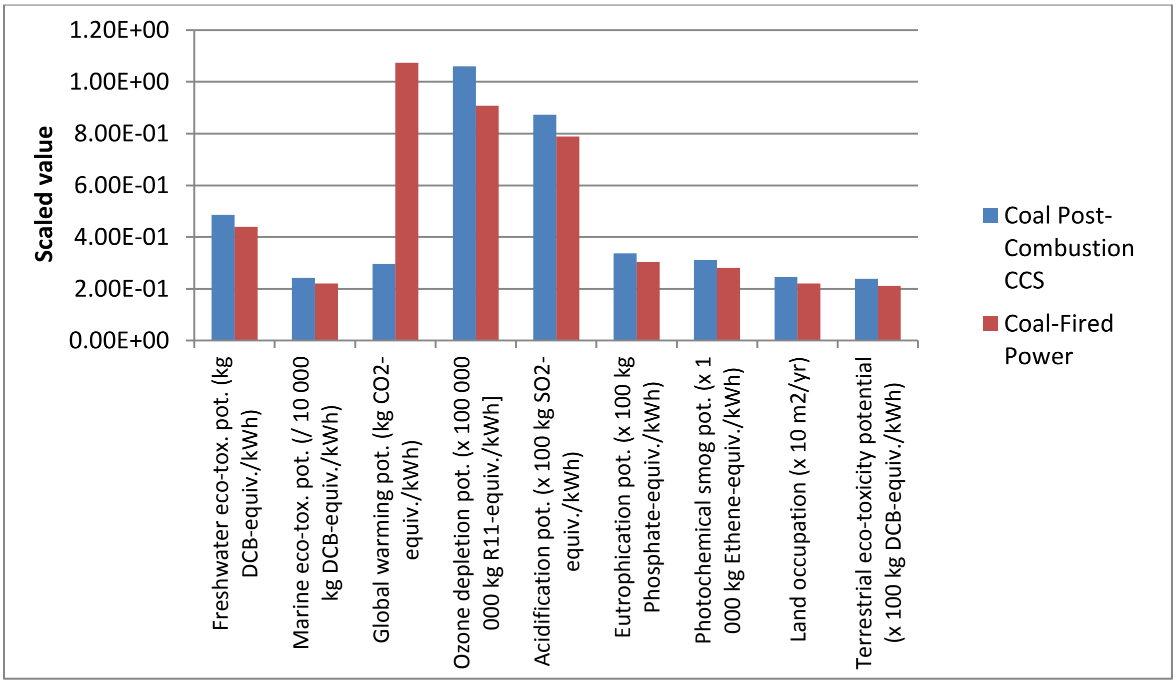


Figure 7.40. Life cycle environmental impacts of a post-combustion coal-fired power plant with transport and storage of CO_2 compared to a pulverised coal-fired power plant. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.2.7 Material recyclability

The material recyclability of the CCS power plant is estimated to be around 99% (when averaging the recyclable materials used in construction by weight). Coal power stations use proportionally much less concrete than nuclear reactors. Concrete has a recyclability rate on average, of 80% (Stamford, 2012). However, a coal fired power station (in this case one with carbon capture capability) is composed of proportionally much more steel (98%), which has a recyclability rate of around 100% (Stanford, 2012). This value is similar to the recyclability of a coal-fired power station without CCS capability as the extra materials needed in the construction of a CCS plant is of a similar factor for all materials used.

7.2.5.2.8 Water eco-toxicity

The freshwater eco-toxicity impacts of coal-fired power and coal-CCS power are 4.39 and 4.86 x 10^{-1} kg DCB-equivalent/kWh. The freshwater eco-toxicity result for the CCS power station is 10.6% higher than the result for the coal-fired power station (see Figure 7.41). The majority of the impact of this indicator comes from the mining and coal supply life cycle stage (97%). The coal-fired power station LCA shows that 98% of the total freshwater toxicity potential comes from mining and supply of coal. This figure is proportionally slightly lower in the CCS life cycle as the construction impact for this indicator contributes more as more materials are used to build the carbon capture infrastructure and there is additional waste to be disposed of which are the products of combustion (more coal is burned per kWh due to the energy penalty for CCS) and the CO_2 capture process.

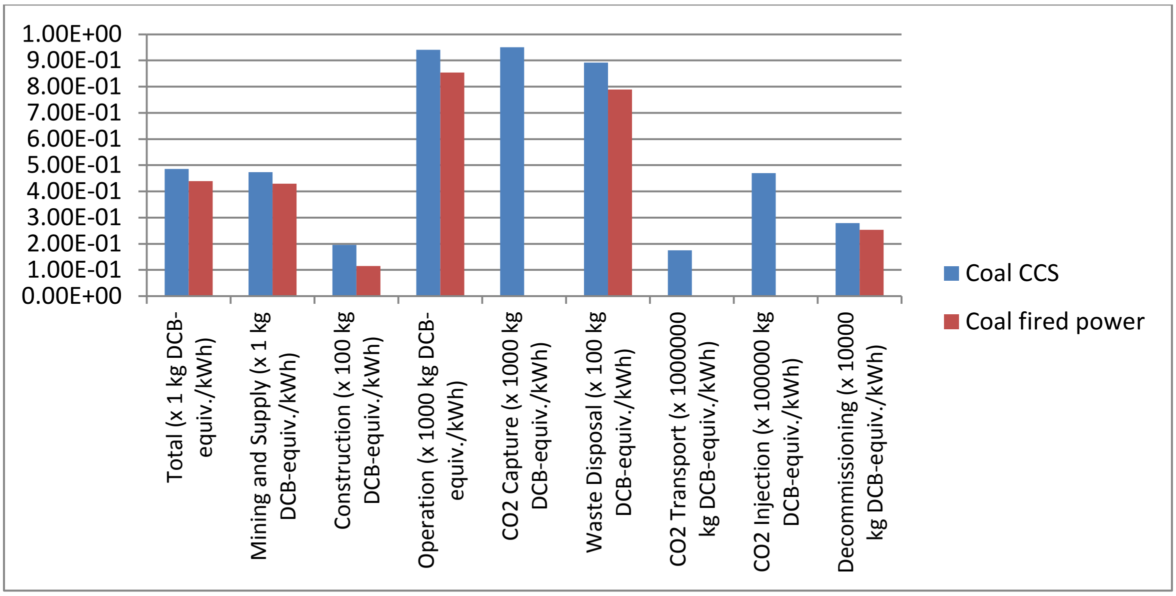


Figure 7.41. Life cycle impact of freshwater eco-toxicity potential for post-combustion coal-fired power plant with transport and storage of CO_2 compared to a pulverised coal-fired power plant. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Coal CCS has a marine eco-toxicity potential greater than coal-fired power, with values for this impact calculated to be 2433 and 2203 kg DCB-equivalent/kWh, respectively. The majority of the marine eco-toxicity result for the CCS life cycle comes from the combustion process (55.5%), followed by coal mining and supply (43.5%) (displayed in Figure 7.42). For a coal-fired power station, the marine eco-toxicity impact comes from the combustion of coal (55.5%) and the coal mining and supply process (44%), which are very similar to the CCS life cycle results for marine eco-toxicity. As more coal is needed for coal-fired power with CCS capability, the impact from mining and from combustion is proportionally similar to coal-fired power without CCS.

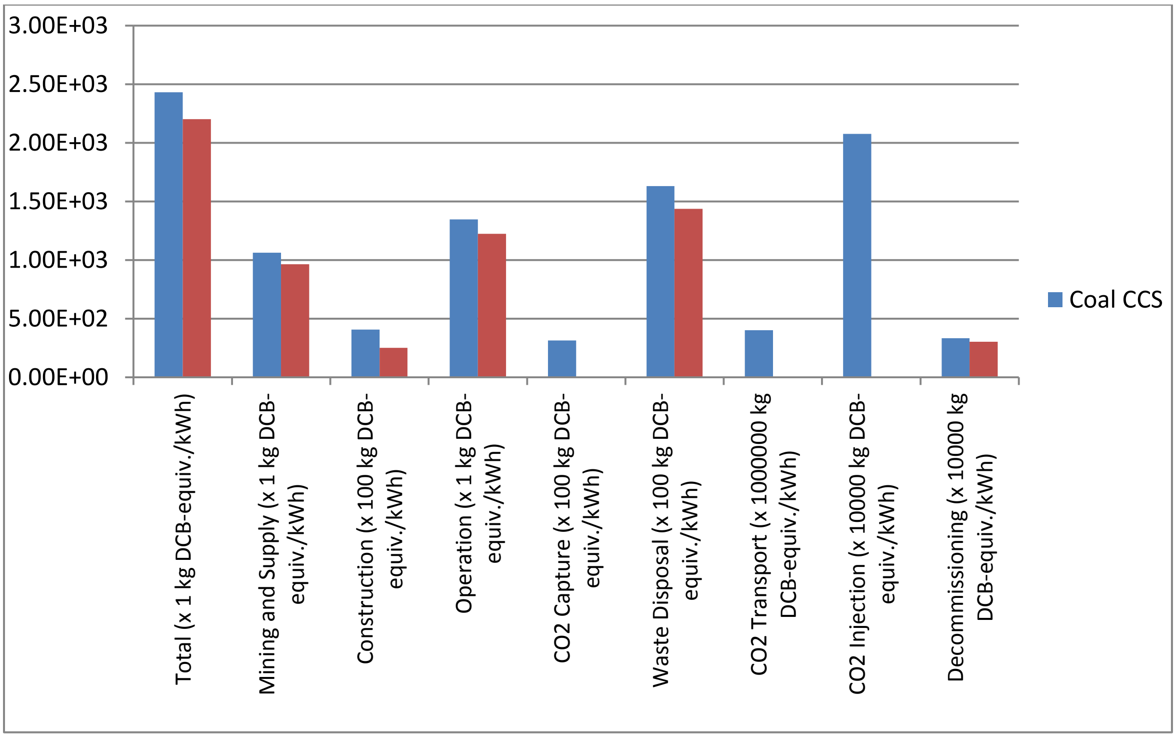


Figure 7.42. Life cycle impact of marine eco-toxicity potential for post-combustion coal-fired power plant with transport and storage of CO_2 compared to a pulverised coal-fired power plant. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.2.9 Global warming potential

The implementation of carbon capture technologies is purely based on the ability to continue to use coal (and to a lesser extent natural gas) as a fuel in electricity generation with minimisation of the global warming potential (GWP) of these technologies.

Over the whole life cycle, the CCS power plant has a GWP that is 28% of the GWP for a pulverised coal-fired power station (per kWh the CCS life cycle has a GWP of 296 g CO_2 and coal fired power has a GWP of 1073 g CO_2 per kWh) (see Figure 7.43). In the combustion stage of the CCS life cycle, 90% of carbon emissions are captured. However, overall carbon emissions are not reduced by this factor as emissions occur at other stage of the life cycle. From analysis of the post-combustion CCS life cycle, the contributions to GWP are from the combustion and CO_2 capture processes (52.5%) and the mining and supply of coal (44.5%). By comparison, 89% of the GWP for a coal-fired power station's life cycle is from the combustion process. The CCS life cycle also has additional GHG emissions from the construction (as more materials are needed for the added CO_2 capture infrastructure), decommissioning (as there are more materials to be disposed of) and waste disposal life cycle stages (more waste is generated in the CCS life cycle due to the added CO_2 capture process). In addition, the CO_2 transport and injection stages are extra stages which contribute to the overall GWP, although both of these life cycle stages are very small in comparison to the others (3 x 10^{-5}% and 0.63%, respectively).

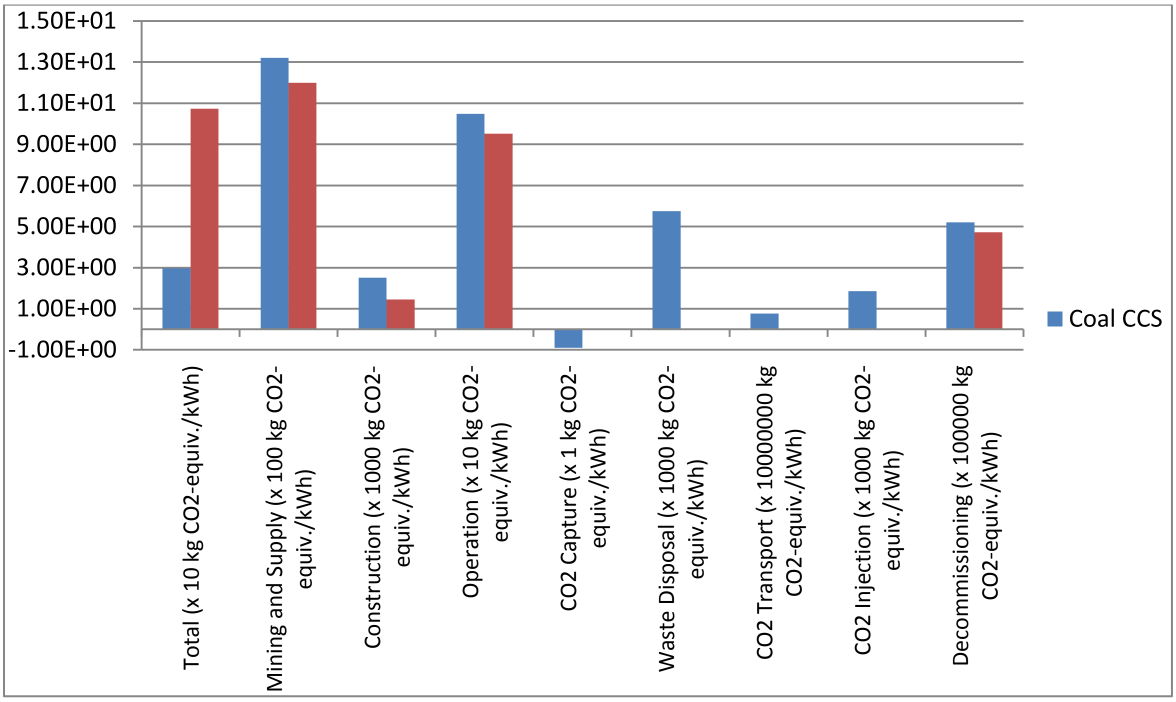


Figure 7.43. Global warming potential (GWP) life cycle impact for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.2.10 Ozone layer depletion potential

The ozone layer depletion potentials for coal CCS and coal-fired power are 1.06 x 10^{-8} and 0.08 x 10^{-9} kg R11-equivalent/kWh, respectively. The ozone layer depletion potential (ODP) impact is 17% larger for the CCS life cycle compared to the life cycle of the coal-fired power station. The ODP for coal-fired power is attributed to coal mining and supply (96%) and most of the remainder is attributed to the operation life cycle stage (3%). The ODP for coal CCS power is attributed to the coal mining and supply life cycle stage (90.5%) and the CO_2 capture process (4.5%). The addition of the CO_2 capture life cycle stage proportionally decreases the contribution of the coal mining and supply life cycle stage to the ODP indicator. Within the CO_2 capture stage, the use of the monoethanolamine solvent contributes 84% to the ODP of this individual life cycle stage. Additional mining and supply of coal also increases the emissions that contribute to ODP for the CCS life cycle. The results for the coal CCS and coal-fired power impacts for ODP are displayed in Figure 7.44.

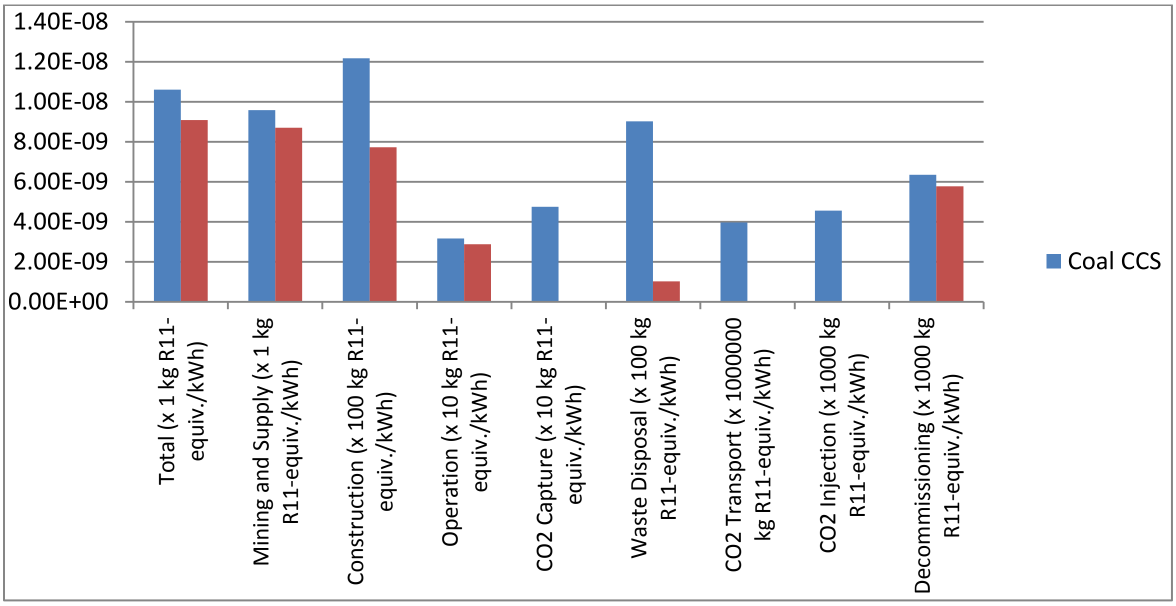


Figure 7.44. Ozone layer depletion potential (ODP) life cycle impact for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.2.11 Acidification potential

The acidification potential (AP) for coal CCS is 8.73 x 10^{-3} kg SO_2-equivalent/kWh, which is 10.5% higher than the impact for the coal-fired power station (7.89 x 10^{-3} kg SO_2-equivalent/kWh). These results are displayed in Figure 7.45. The main contribution of the acidification potential for coal-fired power comes from the operation stage of the life cycle (77%) and specifically the combustion of the coal. In the CCS life cycle, again 77% of the acidification potential comes from the operation stage of the life cycle. The higher AP impact is therefore mostly a result of the energy penalty of the CCS life cycle. There are also higher impacts from construction as extra materials are used to build the CCS power station, coal mining and supply and decommissioning. The CO_2 capture system also contributes to the raised AP of the CCS life cycle through the use of the monoethanolamine solvent compared to the coal-fired power life cycle.

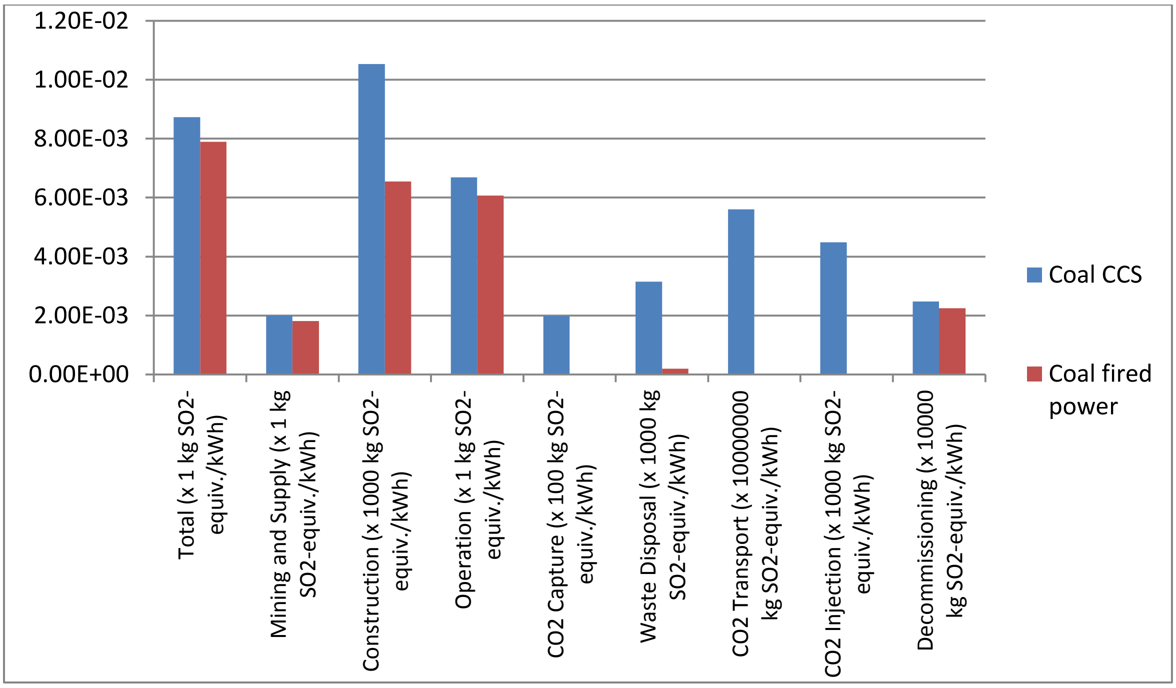


Figure 7.45. Acidification potential (AP) life cycle impact for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.2.12 Eutrophication potential

The eutrophication potential (EP) impacst for coal CCS and coal-fired power are 3.37 x 10^{-3} and 3.04 x 10^{-3} kg phosphate-equivalent/kWh. The coal CCS life cycle is 10.7% higher than the coal-fired power life cycle (see Figure 7.46). For coal-fired power, the contribution to EP comes mainly from mining and supply of coal (just over 91%), which is very similar to the CCS life cycle (just under 91%). The absolute value for EP from power generation from the CCS life cycle is higher due to the increased use of coal because of the energy penalty encountered in power generation in which carbon capture is used - more mining and supply of coal needs to occur to provide more coal per kWh. In addition, the contributions of construction, combustion, decommissioning and waste disposal to EP also rise. The CO_2 capture life cycle stage contributes marginally (0.26%) to the overall EP value.

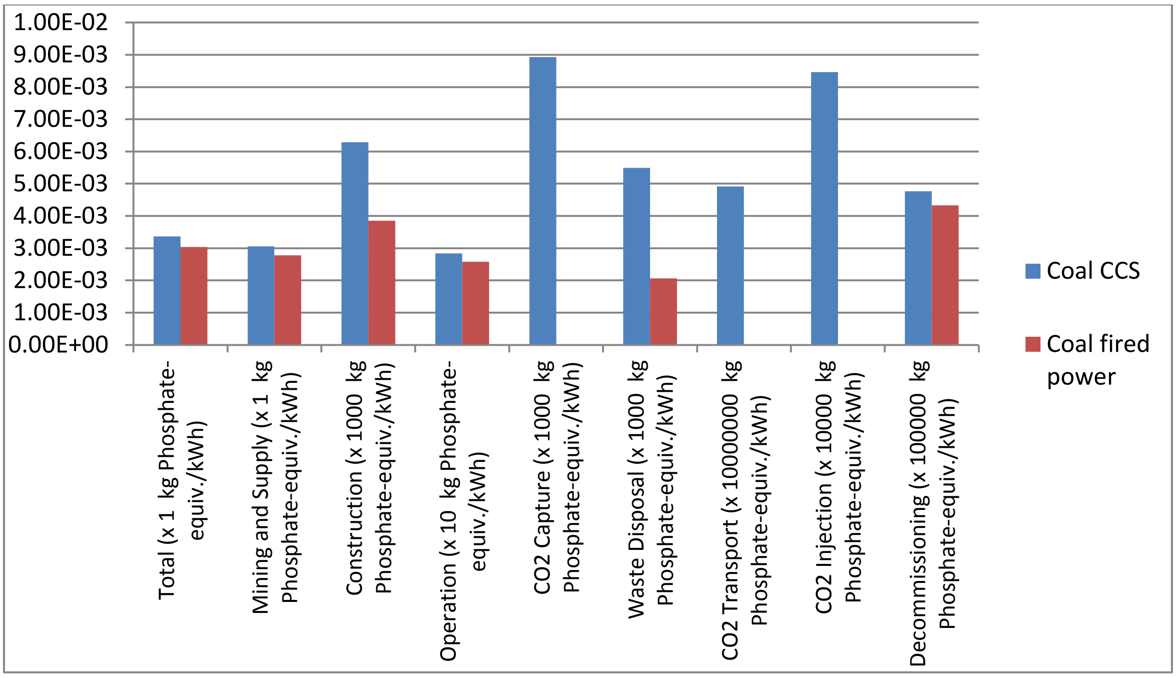


Figure 7.46. Eutrophication potential (EP) life cycle impact for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.2.13 Photochemical smog creation potential

The photochemical smog potential (POCP) result for the coal-fired power station is 2.8 x 10^{-4} kg ethane equivalent, compared to 3.11 x 10^{-4} for coal-fired power with CCS. This is a rise of 11% for coal-fired power with CCS. The main life cycle contribution to POCP in the coal life cycle without CCS is the operation (mainly combustion) of coal. Operation makes up 79.5% of POCP and combustion contributes just under 100% of the operational impact. The coal CCS life cycle shows that 79% of the POCP is from the operation stage of the life cycle. Therefore, the higher resultant POCP is mostly due to an increase in the amount of coal combusted per kWh of electricity generation from coal power with CCS. These results are displayed in Figure 7.47.

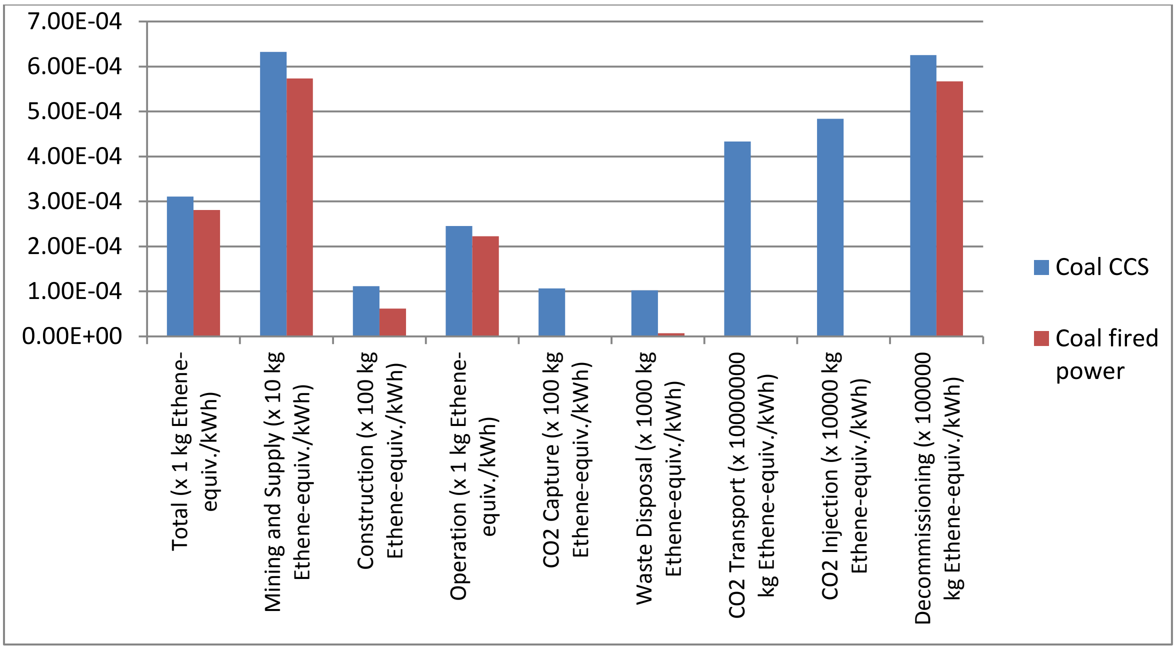


Figure 7.47. Photochemical smog creation potential (POCP) life cycle impact for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.2.14 Land use and quality

Land occupation for coal-fired power is 2.2 x 10^{-2} and for coal power with CCS land occupation is 2.5 x 10^{-2} (m^2/yr). This is an increase of 10.7% land occupation for coal CCS. The land occupation for coal power is attributed mostly to the mining and supply of coal (99.5%). For coal CCS, land occupation for mining and supply of coal contributes 98.8% to this indicator. See Figure 7.48 for a graphical representation of these results. The increase in the absolute value for land occupation for coal CCS is therefore mostly due to the increased coal supply for this life cycle.

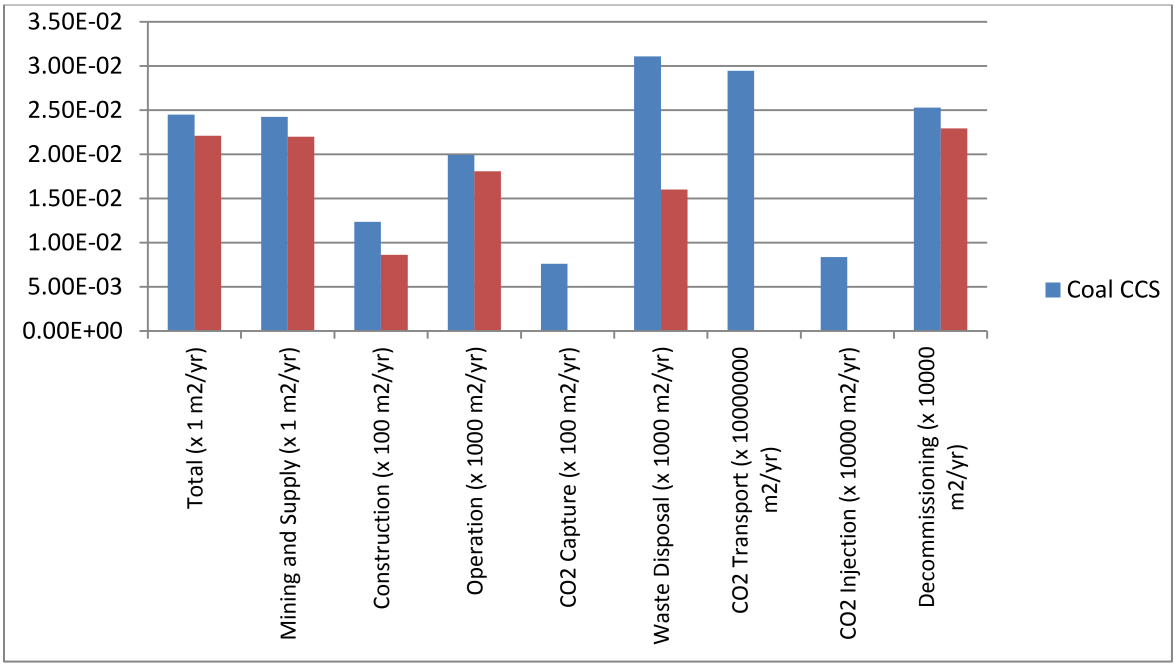


Figure 7.48. Land occupation life cycle impact for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

From study of the most up to date information on plans to build coal-fed CCS power stations in the UK, it can be determined that currently, there are plans to build five new coal-fed CCS plants in the UK. These sites include: C.Gen's Killingholme site; Caledonia Clean Energy's project at the Port of Grangemouth, Progressive Energy's site in Teeside; the Don Valley Project in Stainforth; and White Rose Capture Power Limited's site in Selby (CCSA, 2012). All of the above proposed sites are on brownfield sites that are either on existing coal power stations sites or on brownfield land adjacent to existing power station sites. Therefore, at present, 100% of coal CCS proposals will be constructed on brownfield land, meaning that greenfield land will not be compromised from current proposals.

The terrestrial eco-toxicity potential (TETP) for coal CCS is 12.8% higher than for a coal-fired power station. The absolute values for coal CCS and coal without CCS are 2.39 x 10^{-3} and 2.12 x 10^{-3}, respectively (see Figure 7.49). TETP for the coal life cycle without CCS is attributed mostly to the operation stage (78%) and to the coal mining and supply stage (21%). The coal CCS life cycle shows that 76% of its TETP comes from the operation stage of the coal CCS plant and 20.5% comes from the coal mining and supply stage. An increase in TETP for coal CCS comes from the increased coal supply and increased combustion per kWh of electricity produced. Construction of the CCS power plant and the CO_2 capture process also contribute to the overall increase in TETP for coal CCS.

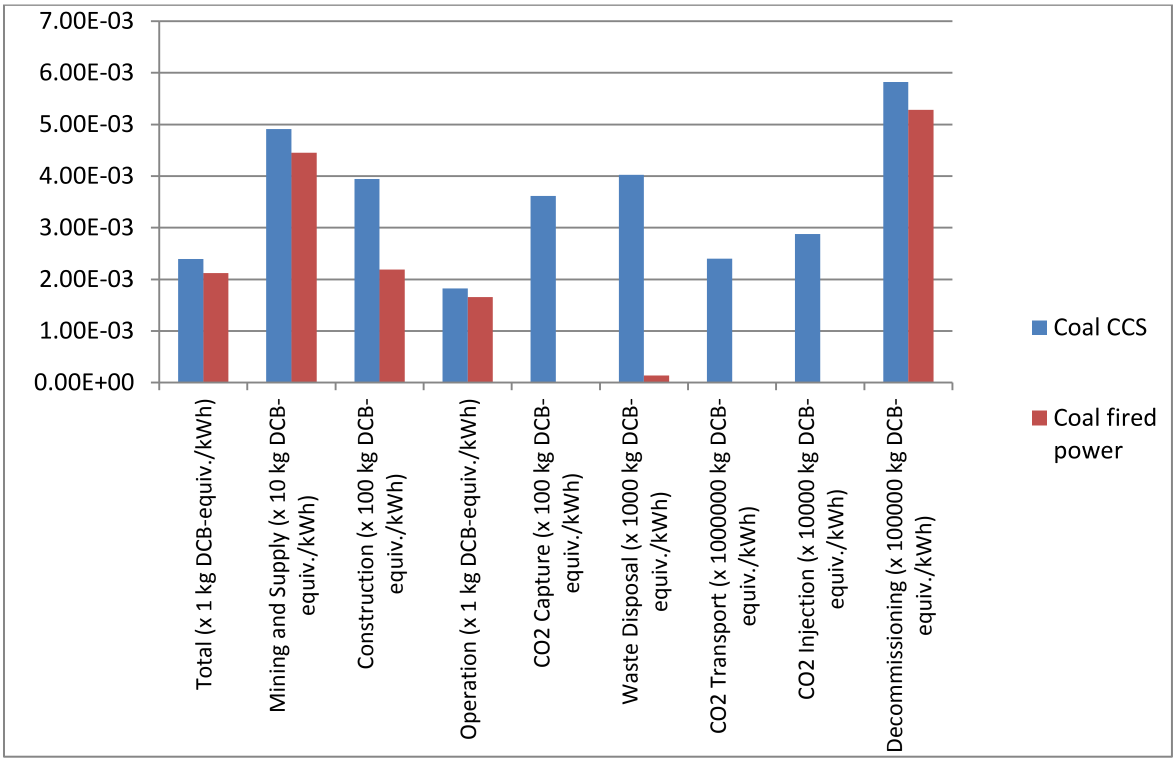


Figure 7.49. Terrestrial eco-toxicity potential (TEP) impact for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.2.15 Comparison and validation of the coal CCS results

As already indicated at the beginning of this section, the LCA results of this coal CCS power station are compared here with the results from NEEDS (2008). As far as the author of this thesis is aware, there are no UK-specific studies in literature that report the full suite of life cycle impacts on a cradle to grave basis for coal CCS power, taking into account the post-combustion method of carbon capture. Here, the results of coal CCS life cycle impacts from NEEDS are compared to the results of the coal post-combustion CCS life cycle modelled within this section.

The results are compared on the basis of the functional unit, ‘1 kWh’. The specific technology compared from NEEDS is a hard coal, 500 MW coal post-combustion power plant, with 400 km of pipeline transport and storage 2 500 m deep in a depleted gasfield and a 90% direct carbon capture rate. The coal CCS life cycle modelled as part of this thesis has taken into account 500 km of pipeline transport and 1 000 m deep geological disposal also with a 90% direct carbon capture rate. The results of this comparison can be seen in Figure 7.50.

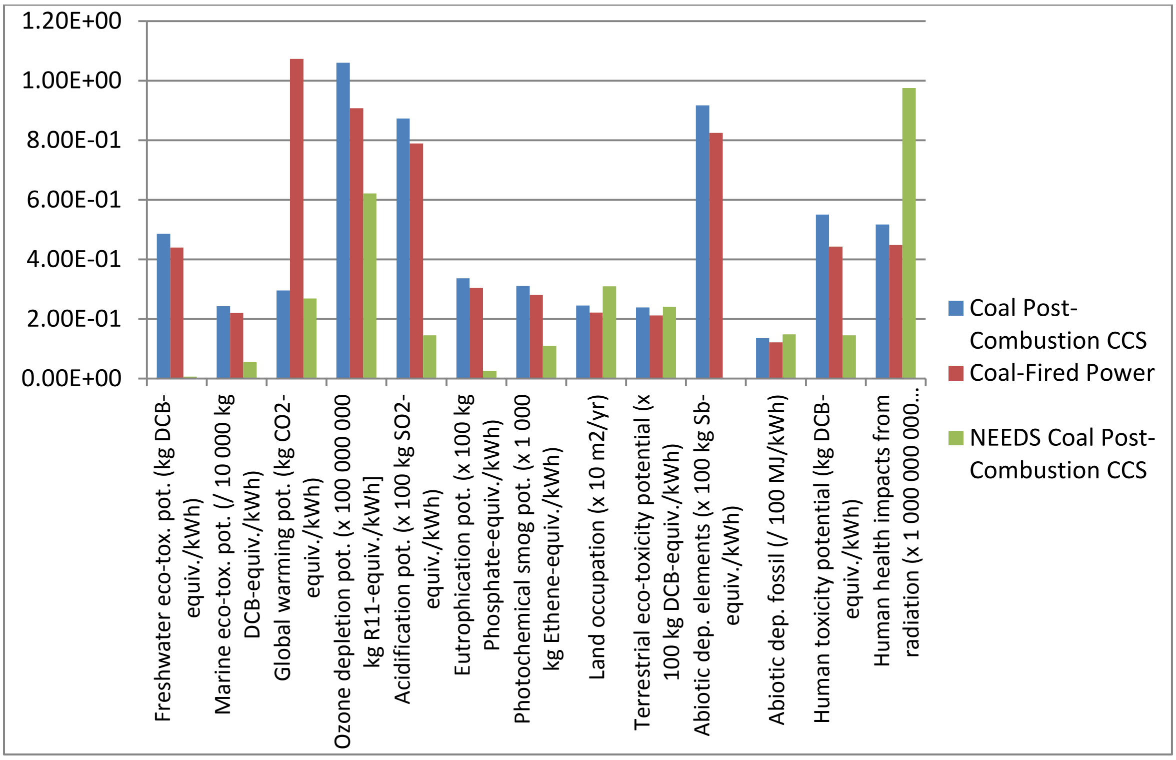


Figure 7.50. Life cycle environmental impacts of post-combustion coal-fired power plant modelled as part of this thesis, a pulverised coal-fired power plant and a post-combustion CCS coal-fired power station modelled as part of NEEDS (2008). [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

As the figure above shows, the results of the coal post-combustion life cycle modelled as part of this thesis display generally higher impacts than the NEEDS coal post-combustion CCS life cycle, with the exception of land occupation, terrestrial eco-toxicity potential and human health impacts from radiation. In many of the impact category results, the value from NEEDS is higher than values from the coal-fired power station. In every case (apart from GWP), it should be expected that the CCS values would be higher than a coal-fired power station, due to extra fuel and materials used across the whole life cycle (this is displayed when comparing the coal CCS and coal-fired power station modelled as part of this thesis).

Several reasons for the differences between the coal CCS power station modelled as part of this thesis and NEEDS coal CCS impact results are apparent. The life cycle assessment carried out within this thesis uses EcoInvent version 2.2 data (EcoInvent, 2010), whilst NEEDS results are calculated using EcoInvent version 1.3 data. Updates to the EcoInvent database have seen significantly altered characterisation factors for the impact categories calculated as part of the life cycle assessments. In addition, NEEDS used European electricity as inputs into their electricity technology models as the project had a European focus. The high level of human health impacts from radiation from NEEDS coal CCS is likely to be due to the higher penetration of nuclear power within the European electricity mix specified, compared to the UK model. Finally, the technology and life cycle characteristics of NEEDS coal CCS power station differ to the life cycle modelled as part of this thesis. The storage is specified as 2 500 m burial and pipeline transport is 400 km, which varies from the 1 000 m storage and 500 km pipeline transport specified in the model developed in this thesis. However, the life cycle stages of NEEDS data cannot be examined in order to determine the relative impacts of each life cycle stage compared to the model developed for this work as NEEDS provide the life cycle data as a full inventory for the whole life cycle, which are not broken down into life cycle stages.

Despite these differences, some of the impact categories do display some agreement, especially for the impact categories: global warming potential, terrestrial eco-toxicity, abiotic depletion of fossil fuels and land occupation. For other impacts, NEEDS data display lower impacts than the coal-fired power station modelled within this thesis, which indicates that the characterisation for these impacts differs from the latest EcoInvent data used within this work.

7.2.5.3 Social sustainability

The results of the social sustainability assessment are discussed below under the following headings of the social sustainability issues: provision of employment; human health impacts; large accident risk; local community impacts; human rights and corruption; energy security; nuclear proliferation; and intergenerational equity.

7.2.5.3.1 Provision of employment

Provision of employment is measured through the use of two indicators: direct employment and total employment (which encompasses direct and indirect employment). Direct employment is a measure of employment created across the whole life cycle of power generation. Total employment is a sum of direct employment and indirect employment, which measures employment created across supply chains which exist because of an electricity-generating installation’s operation.

The methodology for calculation of the employment indicators was developed by Stamford (2012), who also calculated the employment for coal-fired power with CCS capability. Therefore, the figures from this assessment have been used in order to maintain consistency in calculation across the technologies assessed in this work and the technologies assessed in the thesis of Stamford (2012). This is especially important as technologies from both this work and that of Stamford (2012) are assessed as part of future UK electricity scenarios in Chapter 8.

Stamford (2012) assumed that employment within the coal CCS sector would be around 25% higher than coal-fired power over the lifetime of generation. This assumption is based on the increased complexity of operating coal CCS and transporting and storing CO_2. A value of 56.45 person-yrs/TWh is used for direct employment and a value of 214.2 person-yrs/TWh is used for total employment. For more information on the assumptions and data used to calculate this figure, see Stamford (2012).

7.2.5.3.2 Human health impacts

Human health impacts are measured by three indicators: worker fatalities; human toxicity potential; and human health impacts from radiation. The latter two indicators are calculated using the CML methodology in the GaBi LCA software over the whole life cycle of electricity generation. Human toxicity potential is a measure of substances that could potentially harm humans, such as heavy metals. Human health impacts from radiation is a measure of the effect of radiation on the population expressed in disability adjusted life years (DALY).

The value of 2.48 injuries/TWh is used for worker fatalities for coal CCS (Stamford, 2012).

Human toxicity potential

Over the whole life cycle, the coal-fired carbon capture power station has a human toxicity potential that is 24.2% higher than the HTP for a pulverised coal-fired power station (per kWh the CCS life cycle has a HTP of 0.55 kg DCB-equivalent and coal fired power has a HTP of 0.44 kg DCB-equivalent per kWh). Figure 7.51 displays the life cycle impacts of coal-fired power with and without CCS, broken down by life cycle stage. Coal-fired power with carbon capture has a higher impact for HTP in every life cycle stage compared the coal-fired power without carbon capture.

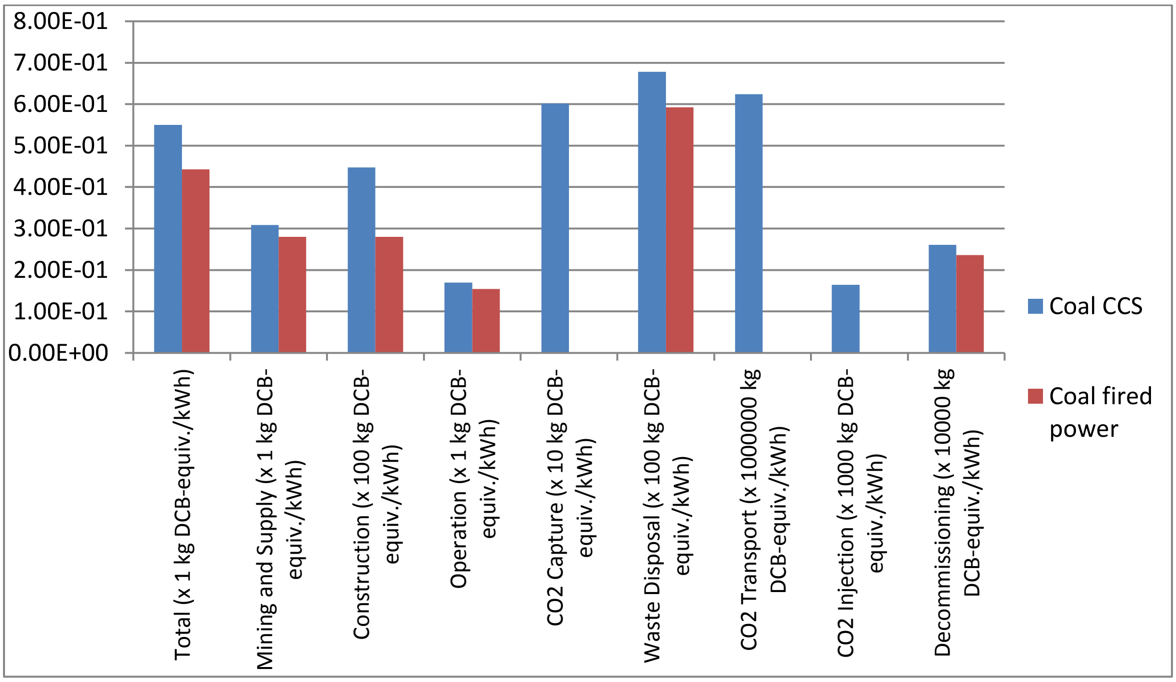


Figure 7.51. Human toxicity potential (HTP) life cycle impact of coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Human health impacts from radiation

Human health impacts from radiation total 5.17 x 10^{-10} DALY per kWh for coal-fired power with CCS and 4.48 x 10^{-10} DALY per kWh for coal-fired power without CCS over the whole life cycle. The coal-fired carbon capture power station has a human health impact from radiation that is 15.3% higher than that for a pulverised coal-fired power station. Figure 7.52 displays the life cycle impacts of coal-fired power with and without

CCS, broken down by life cycle stage. Coal-fired power with carbon capture has a higher impact for human health impacts from radiation in every life cycle stage compared the coal-fired power without carbon capture.

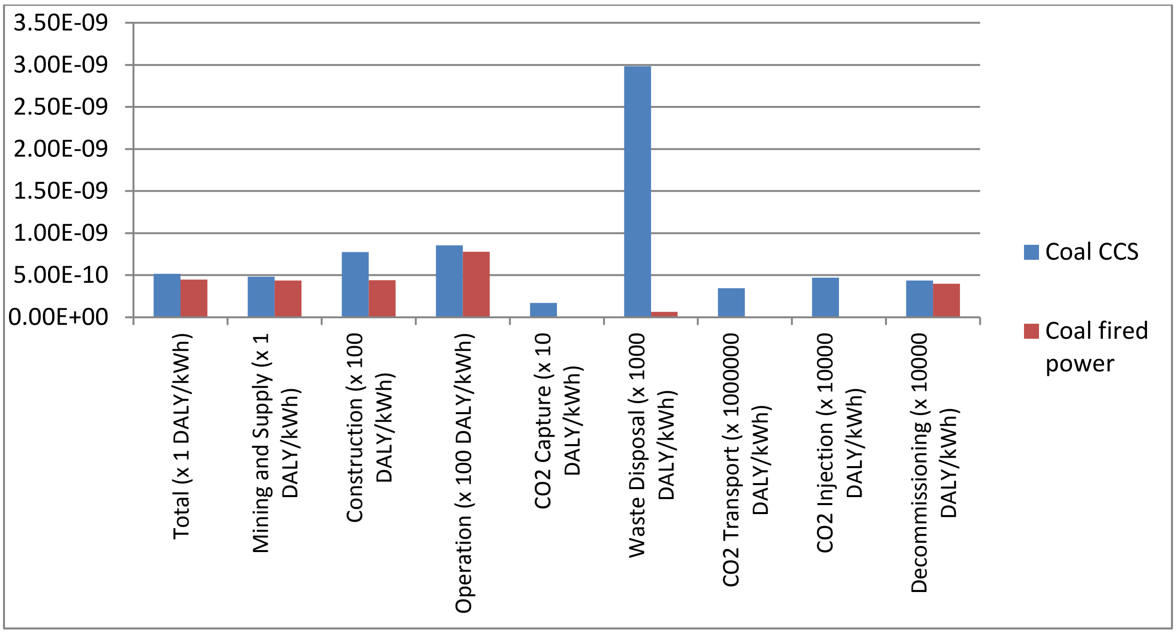


Figure 7.52. Human health impacts from radiation life cycle impact of coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.5.3.3 Large accident risk

This measure of large accident risk is calculated from the loss of life due to large accidents associated with a particular technology. The perspective of this measurement is partly historical, with data used from the OECD's reporting and also partly on probabilistic safety assessments.

The data for large accident risk for CCS is based on work carried out by the Paul Scherrer Institut (Burgherr, P. *et al.*, 2008) and the estimated value for this indicator for coal CCS is 20.56 fatalities/PWh (Stamford, 2012).

7.2.5.3.4 Local community impacts

The impact that a power station or electricity-generating installations might have on the local community within or near to which it operates is assessed using three indicators:

proportion of staff hired from the local community in relation to the total staff; spending on local suppliers relative to total spending on suppliers; and direct financial investment in the local community as a proportion of total annual profits. These indicators do not cover the whole life cycle and refer only to the operation stage of electricity-generation. This is primarily due to sufficient and reliable information being available on the remaining life cycle stages. This indicator has not been considered for this sustainability assessment as the measures are company-specific and the operation companies for all of the technologies evaluated are not currently known.

7.2.5.3.5 Human rights and corruption

Human rights violations and corruption are measured by through the use of the Transparency International Corruption Perceptions Index (Transparency International, 2011). Within this index, countries are scored on a scale of 0-10 based on the level of corruption exhibited by national officials. A score of 0 indicates extreme corruption and a score of 10 indicates non-corrupt. The average scores of nations involved in the life cycle is taken in order to produce a score for an electricity-generating technology. For coal-fired power with carbon capture, power plant operation, CO_2 transport, injection and storage all take place within the UK. The UK currently sources steam coal (for electricity production) from several countries, and coal is also mined domestically - in 2011 around 16.3 million tonnes of coal were produced in the UK and 26.5 million tonnes were imported from a variety of countries including: Russia, Columbia, the Republic of South Africa and the United States of America, in addition to a number of EU nations and other countries that provided very small amounts of coal to the total amount of coal consumed in the UK (DECC, 2012d). Taking into account all of the countries specified above, an average CPI value of 5 is derived for coal-fired power, with and without carbon capture and storage capability in the UK.

7.2.5.3.6 Energy security

UK energy security is measured using three indicators: amount of fossil fuel potentially avoided; diversity of fuel supply; and fuel storage capability. Decreasing the reliance on the imports of fossil fuels (coal, gas, oil) and increasing the use of energy sources available within the UK could increase the UK's energy security. Diversifying fuel imports to make the UK less dependent on any one country could help increase the UK's energy security. This can also be improved by being able to store fuels for future use. Some fuels are more suited for storage (e.g. solid and liquid fuels) while others are less so (e.g. gaseous fuels).

The first indicator of energy security (amount of fossil fuel potentially avoided) is not applicable to fossil fuel power stations and therefore coal-fired power with and without carbon capture scores zero under this measure.

The diversity of the UK's coal supply is calculated by using Simpson's Index of Diversity (SID) (see Stamford and Azapagic (2011) for the methodology), which calculates an index of diversity based on the richness of the supply of fuel (i.e. the number of suppliers) and the evenness of that supply spread between each supplier. The calculated SID is then used to determine the diversity of fuel supply (DFS) through multiplication this value by the proportion of fuel supplied from imports, added to the supply of fuel that is provided indigenously. The overall DFS for coal used in coal-fired power stations in the UK (for the year 2011) is 0.78 (with a score of 1 representing a diverse fully supply and a score of 0 representing a fuel supply that is overly reliant on one nation for its supplies).

The final indicator used to determine energy security of a particular electricity-generating method is the fuel storage capability measure. Ability to stockpile and store for suture use would mean that the UK would be less vulnerable to import shortages arising from disruptions in supply chains of fuels. Here, this indicator is expressed in terms of energy content of the fuel per unit mass of fuel stored. This indicates fuel storage needs for different types of fuels. The energy density of coal has been calculated to be 21 GJ/m^3 (Stamford and Azapagic, 2011). As coal-fired power with carbon capture induced an energy penalty of around 10.2% (IPCC, 2005), this means that the energy needed to produce the same amount of electricity as from a traditional coal-fired power station increase and therefore the energy density of coal for use in carbon capture power stations decreases to 18.6 GJ/m^3.

7.2.5.3.7 Nuclear proliferation

The measure of nuclear proliferation of nuclear technologies is measured using three components to this indicator: use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; and requirement for enriched uranium. Nuclear proliferation is defined as the use nuclear weapons or the spread of weapons technology and therefore the measures proposed seek to identify technologies that are particularly at risk of proliferation. This indicator is not relevant to the CCS life cycle as no nuclear fuels need to be used to generate electricity using this method or at any stage along its life cycle.

7.2.5.3.8 Intergenerational equity

Intergenerational equity is defined as problems created for future generations to manage. Depletion of resources and long-lived hazardous waste are obvious issues associated with future generations. Climate change is another issue that will affect people many generations into the future, however, this issue is addressed under the global warming potential indicator under the environmental set of measures. Here, intergenerational equity is defined through the use of several measures: use of abiotic elemental resources; use of abiotic fossil resources; volume of radioactive waste to be stored; and volume of liquid CO_2 to be stored.

Depletion of abiotic elemental resources

Use of abiotic elemental resources totals 9.17 x 10^{-3} kg Sb-equivalent per kWh for coal-fired power with CCS and 8.25 x 10^{-3} kg Sb-equivalent per kWh for coal-fired power without CCS over the whole life cycle. The coal-fired carbon capture power station depletes abiotic resources 11.2% more than that for a pulverised coal-fired power station. Figure 7.53 shows the life cycle impacts of the use of abiotic elemental resources for coal-fired power with and without CCS, broken down by life cycle stage. Coal-fired power with carbon capture has a higher impact on the use of abiotic elemental resources in every life cycle stage compared the coal-fired power without carbon capture.

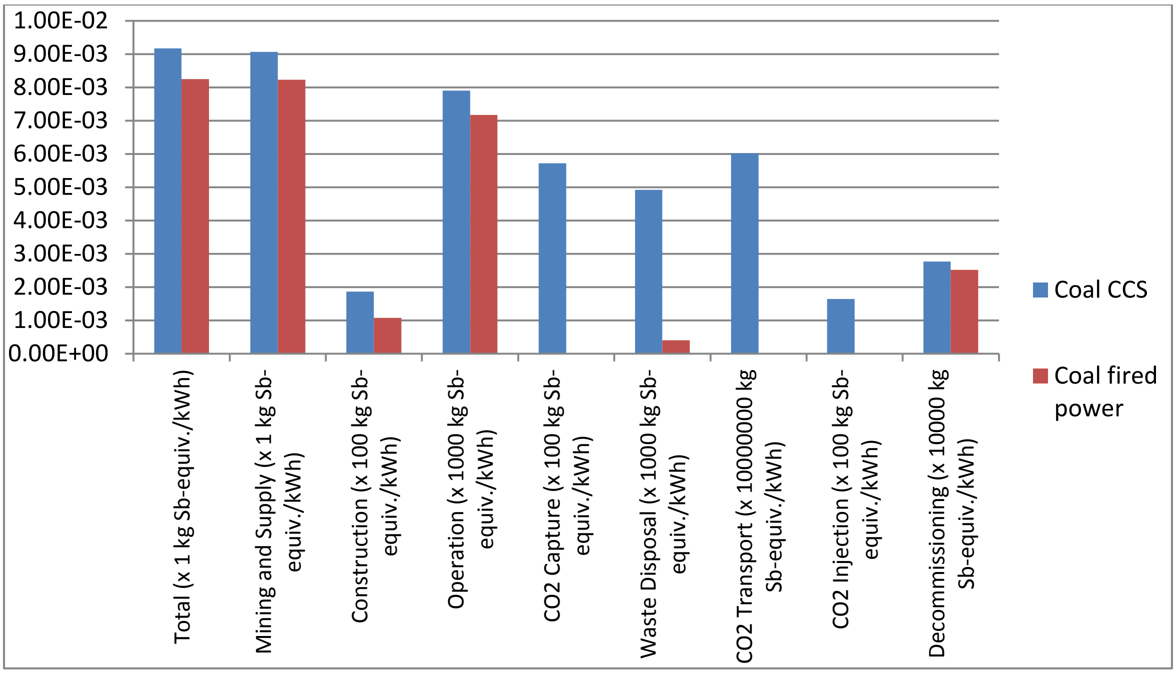


Figure 7.53. Full life cycle impact of the use of abiotic elemental resources for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Depletion of abiotic fossil fuel resources

Use of fossil fuel resources totals 13.6 MJ per kWh for coal-fired power with CCS and 12.2 kg MJ per kWh for coal-fired power without CCS over the whole life cycle. The coal-fired carbon capture power station depletes fossil fuel at a rate of 11.6% more than that for a pulverised coal-fired power station. Figure 7.54 displays the life cycle impacts of the use of fossil fuel resources for coal-fired power with and without CCS, broken down by life cycle stage. Coal-fired power with carbon capture has a higher impact on the use of fossil fuel resources in every life cycle stage compared the coal-fired power without carbon capture.

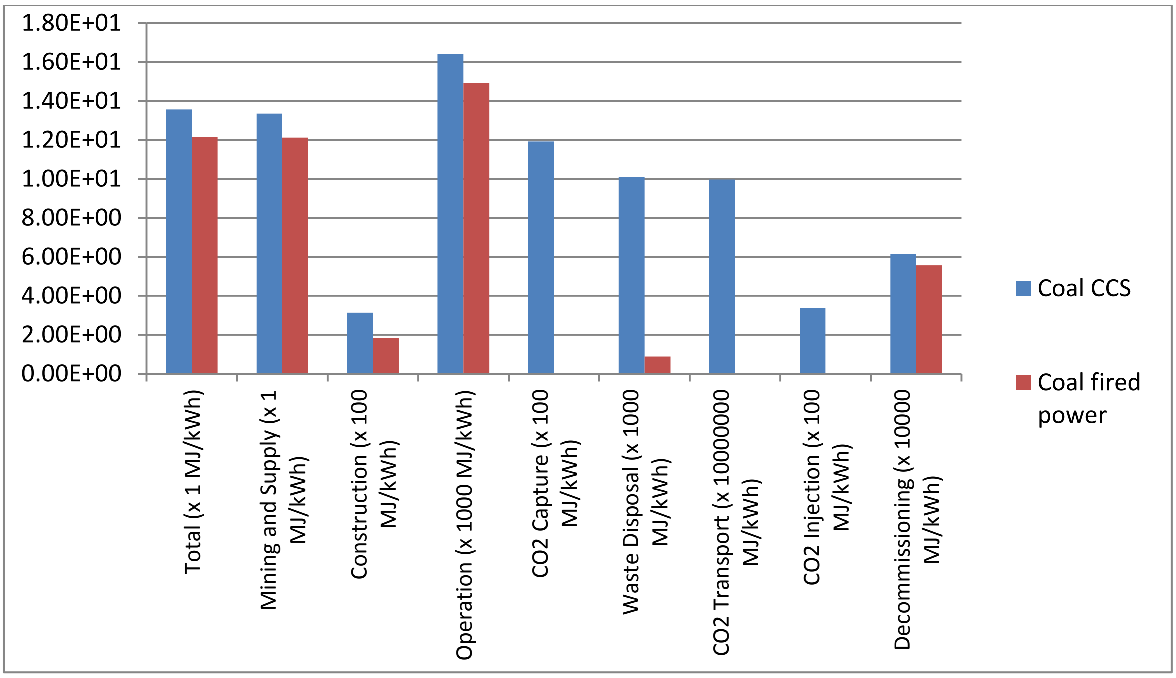


Figure 7.54. Abiotic fossil fuel depletion potential for coal post-combustion carbon capture and storage power and pulverised coal-fired power broken down by life cycle stage. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

Volume of liquid CO_2 to be stored

Direct CO_2 emissions from coal-fired power stations are assumed here to be 790 g CO_2/kWh. A capture rate of 90% for storage within a repository at an injection pressure of 110 bar gives the volume of liquid CO_2 to be stored of 7.48×10^{-4} m^3 CO_2/kWh (Stamford, 2012).

7.2.6 Discussion

This section presents the total sustainability results for all four electricity options considered within this chapter and section 7.2.7 shows how MCDA can be used to help compare these technologies on all the sustainability criteria simultaneously, to help identify the most sustainable technology overall. Techno-economic results are presented first, followed by environmental sustainability results and finally, the social sustainability results. The total life cycle sustainability impacts for the four technologies are summarised in Table 7.3.

7.2.6.1 Techno-economic sustainability

In this section, the techno-economic sustainability of the four competing electricity technologies is presented. The previous sections present the specific results of each technology; this section focuses on a comparison between the technologies. The techno-economic sustainability results for the AP1000, EPR and EFR nuclear reactors and the coal CCS power plant are displayed in Figure 7.55. In terms of power plant operability (measured by the indicators: capacity factor, availability factor, technical dispatchability, economic dispatchability and lifetime of fuel reserves), it can be seen that no one technology dominates the others. The AP1000 and EPR perform best overall with regard to capacity and availability factors, with coal CCS also performing relatively well under these measures. Coal CCS is the most dispatchable technology (displaying the best results for technical and economic dispatchability). The only operability indicator under which the EFR dominates is the lifetime of fuel reserves measure. The EFR also displays preferable values for the technological lock-in measure, along with coal CCS.

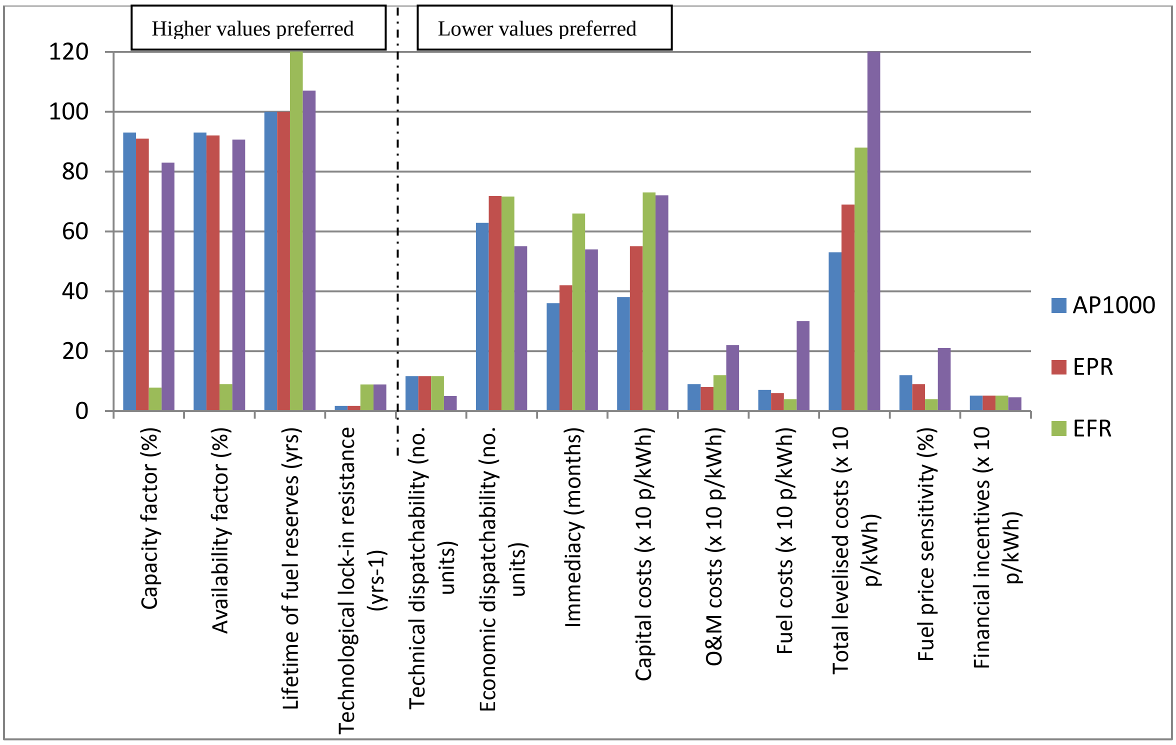


Figure 7.55. Techno-economic sustainability of the AP1000, EPR, EFR and post-combustion coal CCS. For the indicators: capacity factor; availability factor; technological lock-in; and lifetime of fuel reserves, higher values are preferred. For the remainder of the indicators, lower values are preferred. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

The quickest power plant to build is the AP1000, followed by the EPR and then coal CCS and the EFR has the least preferable value in terms of immediacy of power generation. In terms of costs, the AP1000 is the cheapest technology overall to implement on a life cycle basis, followed by the EPR, then EFR and coal CCS. Coal CCS is relatively uncompetitive in terms of capital, fuel and operation and maintenance costs. The EFR has slightly higher capital costs than coal CCS, but has the lowest fuel costs out of all technologies and is least sensitive to fuel price (coal CCS displays the greatest fuel price sensitivity). Financial incentives are greatest under the nuclear technologies due to the lower carbon intensity of this type of electricity generation compared to coal CCS.

7.2.6.2 Environmental sustainability

Figure 7.56 shows the results of the environmental sustainability of the AP1000, EPR, EFR and coal CCS. It can be seen that the EFR displays the most preferable values under nine of the eleven indicators. This is due to the minimisation of the front end fuel cycle impacts within the nuclear fuel cycle as the EFR uses a mixture of spent fuel and uranium for power generation and displays a superior fuel economy compared to the AP1000 and EPR. Coal CCS displays the worst impacts under every indicator, except the greenfield land use and recyclability measures (nine out of eleven indicators). Coal CCS power uses additional fuel to coal-fired power due the energy penalty incurred from the CO_2 capture process. The additional coal combustion carried out in CCS technologies increases the environmental impact for all LCA impact categories compared to coal-fired power (except GWP). Even in terms of GWP of coal CCS compared to the nuclear technologies, coal CCS has a GWP around 60 times higher than the AP1000 and EPR, and around 200 times higher than the EFR. Material recyclability is greatest under coal CCS due to the higher proportion of recyclable metals used in construction of coal CCS power plants, compared to the high se of concrete in nuclear power stations. In addition, at the present, there are no plans to develop coal CCS power stations on greenfield land, meaning that coal CCS also performs well under this indicator.

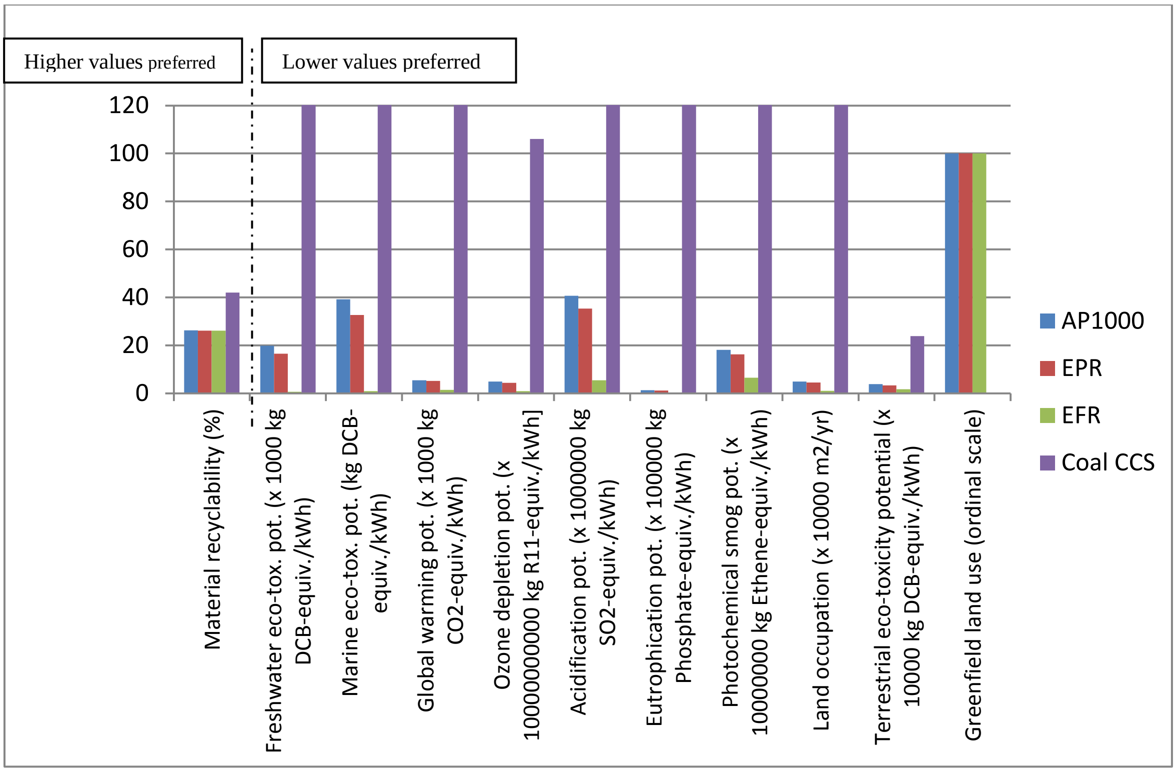


Figure 7.56. Environmental sustainability of the AP1000, EPR, EFR and post-combustion coal CCS. For 'recyclability', higher values are preferred, for all other indicators, lower values are preferred. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

7.2.6.3 Social sustainability

The social sustainability results for the AP1000, EPR, EFR and coal CCS are displayed in Figure 7.56. Coal CCS displays preferable values under five indicators (out of fifteen). These are: nuclear proliferation; radioactive waste storage; human health impacts from radiation, direct and total employment (mostly nuclear-specific measures). Coal CCS displays the worst results under ten of the indicators – these are associated with human health and injuries from toxicity (due to pollutants associated with coal combustion, mining accidents and pollution released from mining, which may affect human health), resource use (fossil and elemental), human rights, CO_2 storage and energy security (fossil fuel avoided and fuel storage). All three nuclear technologies display the same or similar results under many of the measures, although the EFR is the most sustainable option with regard to human rights, diversity of fuel supply, fuel storage capability and human toxicity potential. These indicators are associated with the relatively low resource and fuel use of the EFR compared to the AP1000 and EPR.

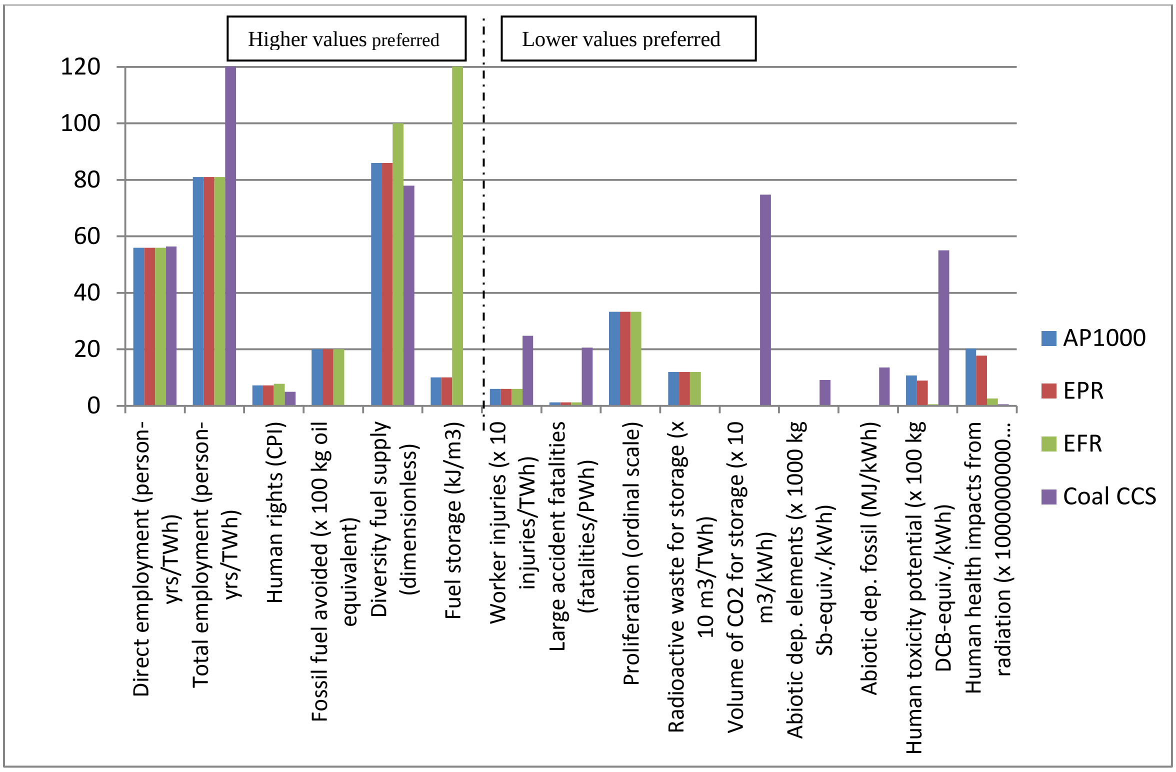


Figure 7.57. Social sustainability of the AP1000, EPR, EFR and post-combustion coal CCS. For the indicators: employment; fossil fuel avoided; diversity of fuel supply; and fuel storage capabilities, higher values are preferred, for the remainder of the indicators, lower values are preferred. [Some indicators have been scaled to fit on the graph. To obtain the original value, multiply or divide the value shown on the graph by the factors shown in brackets.]

From the presentation of the total sustainability results of the AP1000, EPR, EFR and coal CCS, it can be determined that no one technology dominates the others under all sustainability criteria. In an attempt to order these criteria and initiate a dialogue regarding potential trade-offs of sustainability indicators to determine the most sustainable technology, a multi-criteria analysis is carried out in the next section of this chapter.

Table 7.3. Total sustainability results for the AP1000, EPR, EFR and coal CCS technologies. ['Min' after indicators indicates where lower values are preferred, and 'max' indicates where higher values are preferred].

	Indicator	AP1000	EPR	EFR	Coal CCS
Techno-economic	Capacity factor (%) (max)	93	91	7.8	83
	Availability factor (%) (max)	93	92	9	90.7
	Technical dispatchability (no. units) (min)	11.67	11.67	11.67	5
	Economic dispatchability (no. units) (min)	62.85	71.8	71.65	55
	Lifetime of fuel reserves (yrs) (max)	100	100	5000	107
	Technological lock-in resistance (yrs^{-1}) (max)	1.7	1.7	8.9	8.9
	Immediacy (months) (min)	36	42	66	54
	Capital costs (p/kWh) (min)	3.8	5.5	7.3	7.2
	O&M costs (p/kWh) (min)	0.9	0.8	1.2	2.2
	Fuel costs (p/kWh) (min)	0.7	0.6	0.4	3
	Total levelised costs (p/kWh) (min)	5.3	6.9	8.8	13.6
	Fuel price sensitivity (%) (min)	12	9	4	21
	Financial incentives (p/kWh) (min)	0.51	0.51	0.51	0.46
Environmental (all min except material recyclability))	Material recyclability (%) (max)	26.3	26.1	26.1	42
	Freshwater eco-tox. pot. (kg DCB-equiv./kWh)	1.98E-02	1.65E-02	6.51E-04	4.90E-01
	Marine eco-tox. pot. (kg DCB-equiv./kWh)	3.92E+01	3.26E+01	8.60E-01	2.43E+03
	Global warming pot. (kg CO2-equiv./kWh)	5.49E-03	5.12E-03	1.42E-03	2.90E-01
	Ozone depletion pot. (kg R11-equiv./kWh]	4.94E-10	4.34E-10	9.03E-11	1.06E-08
	Acidification pot. (kg SO2-equiv./kWh)	4.07E-05	3.53E-05	5.50E-06	8.73E-03
	Eutrophication pot. (kg Phosphate-equiv./kWh)	1.32E-05	1.12E-05	1.04E-06	3.70E-03
	Photochemical smog pot. (kg Ethene-equiv./kWh)	1.81E-06	1.63E-06	6.48E-07	3.11E-04
	Land occupation (m2/yr)	4.86E-04	4.56E-04	1.10E-04	2.45E-02
	Terrestrial eco-toxicity potential (kg DCB-equiv./kWh)	3.89E-04	3.26E-04	1.68E-04	2.39E-03
	Greenfield land use	1	1	1	0
Social	Direct employment (person-yrs/TWh) (max)	5.60E+01	5.60E+01	5.60E+01	5.65E+01
	Total employment (person-yrs/TWh) (max)	8.10E+01	8.10E+01	8.10E+01	2.14E+02
	Worker injuries (injuries/TWh) (min)	6.00E-01	6.00E-01	6.00E-01	2.48E+00
	Large accident fatalities (fatalities/PWh) (min)	1.22	1.22	1.22	20.56
	Human rights (CPI) (max)	7.2	7.2	7.8	5.0
	Fossil fuel avoided (kg oil equivalent) (max)	2.00E-01	2.00E-01	2.00E-01	0.00E+00
	Diversity of fuel supply (dimensionless) (max)	0.86	0.86	1.00	0.78
	Fuel storage (GJ/m^3) (max)	1.00E+07	1.00E+07	5.00E+08	1.86E+01
	Proliferation (ordinal scale) (min)	0.33	0.33	0.33	0.00
	Radioactive waste for storage (m^3/TWh) (min)	1.20	1.20	1.20	0.00
	Volume of CO_2 for storage (m3/kWh) (min)	0.00	0.00	0.00	7.48
	Abiotic dep. elements (kg Sb-equiv./kWh) (min)	3.94E-05	3.62E-05	1.64E-08	9.17E-03
	Abiotic dep. fossil (MJ/kWh) (min)	7.58E-02	6.90E-02	1.86E-02	1.36E+01
	Human toxicity potential (kg DCB-equiv./kWh) min)	1.07E-01	8.86E-02	4.87E-03	5.50E-01
	Human health impacts from radiation (DALY/kWh) (min)	2.02E-08	1.78E-08	2.55E-09	5.17E-10

7.2.7 Multi-criteria decision-analysis

Multi-attribute value theory (MAVT) has been used for the MCDA (for the methodology, see Chapter 2). The specific MAVT method used in this assessment is the weighted summation method, which is carried out as follows:

- definition of the energy technology alternatives to be compared;
- modelling of the sustainability indicators for each technology alternative;
- comparison of each alternative under each indicator and scoring of each alternative under each indicator (for example, the best performing is given a score of 1, and the worst a score of 0);
- weighting of the criteria; and
- ranking of the alternatives by combining the scores with the preferences and then summing all of these values under each of the energy alternatives.

Different weightings are assumed for the sustainability criteria to find out how that influences the outcome of the analysis. First, all the criteria have been assumed of equal importance, followed by assuming in turn high importance of techno-economic, environmental and social criteria. Due to a lack of data, 39 out of 43 indicators have been considered (the local community measures and the radiation exposure to workers are not considered). Of these, 13 are techno-economic, 11 are environmental and 15 are social.

Web-HIPRE version 1.22 (Mustajoki and Hamalainen, 2000) has been used to perform the MCDA (www.hipre.hut.fi/). Figure 7.58 shows part of the decision tree built to compare the sustainability of the technologies considered.

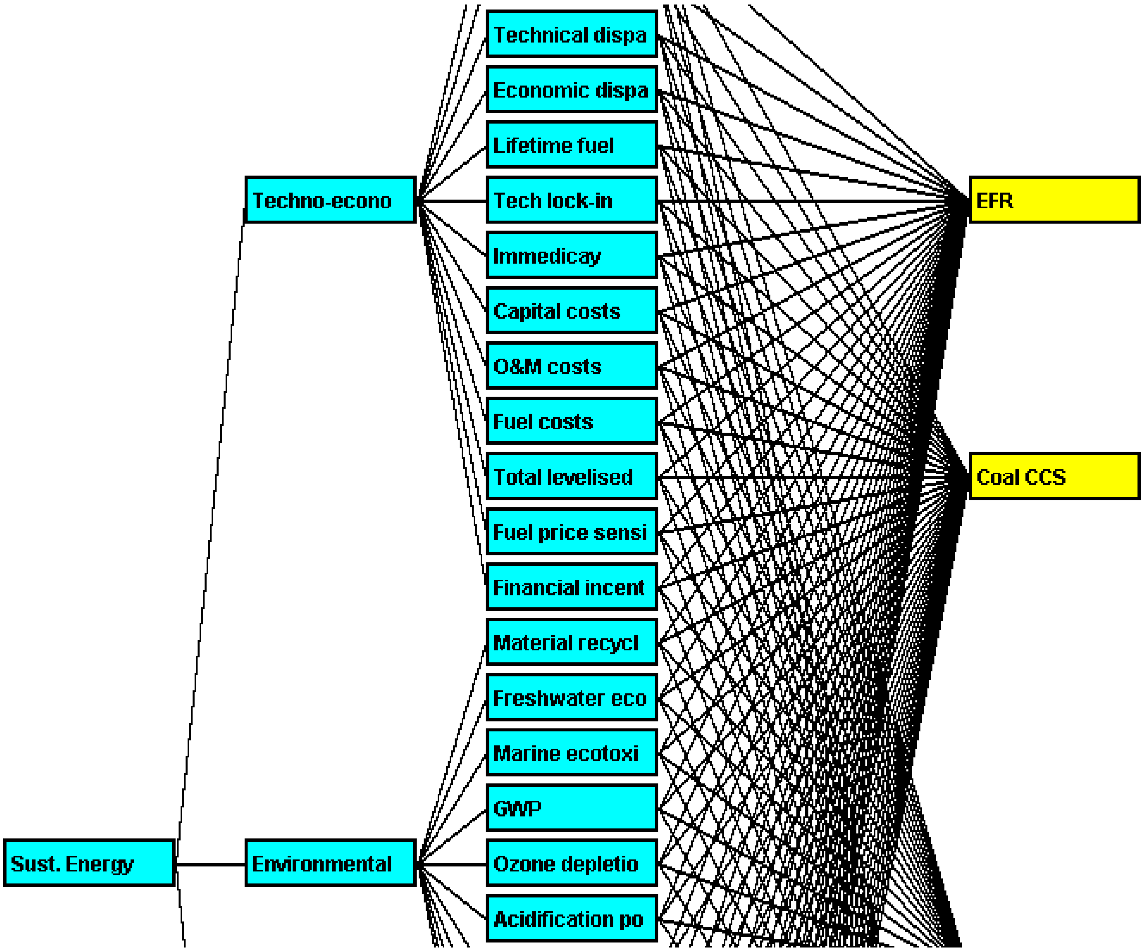
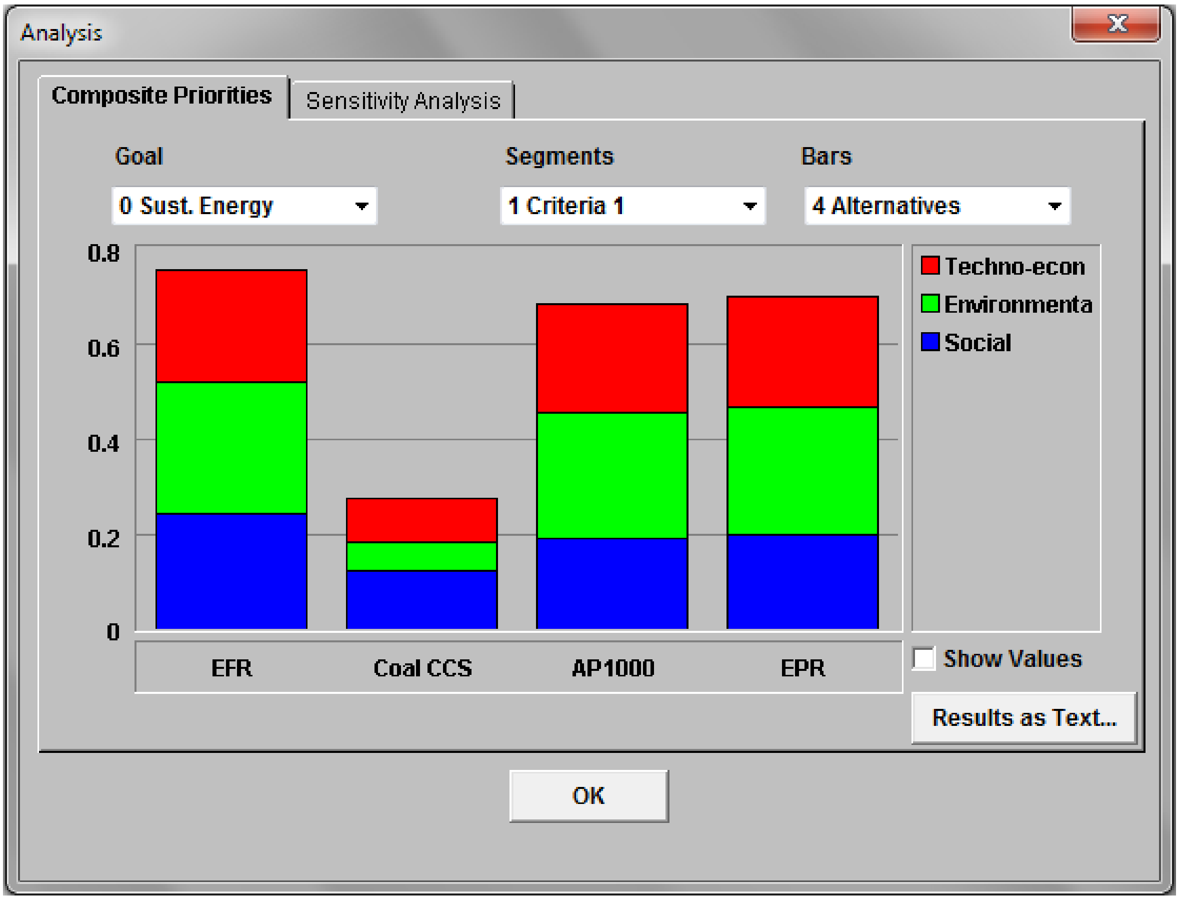


Figure 7.58. Screen shot of a part of the decision-tree built in Web-HIPRE, based on Table 7.3.

The results for the same weighting on all the sustainability criteria are shown in Figure 7.59. As indicated, the EFR is the preferred option, scoring 0.76 (a higher score indicates a more preferable option), followed by the EPR (score of 0.7), which is closely followed by the AP1000 reactor (0.68). The coal CCS is the least preferred option, scoring 0.28.



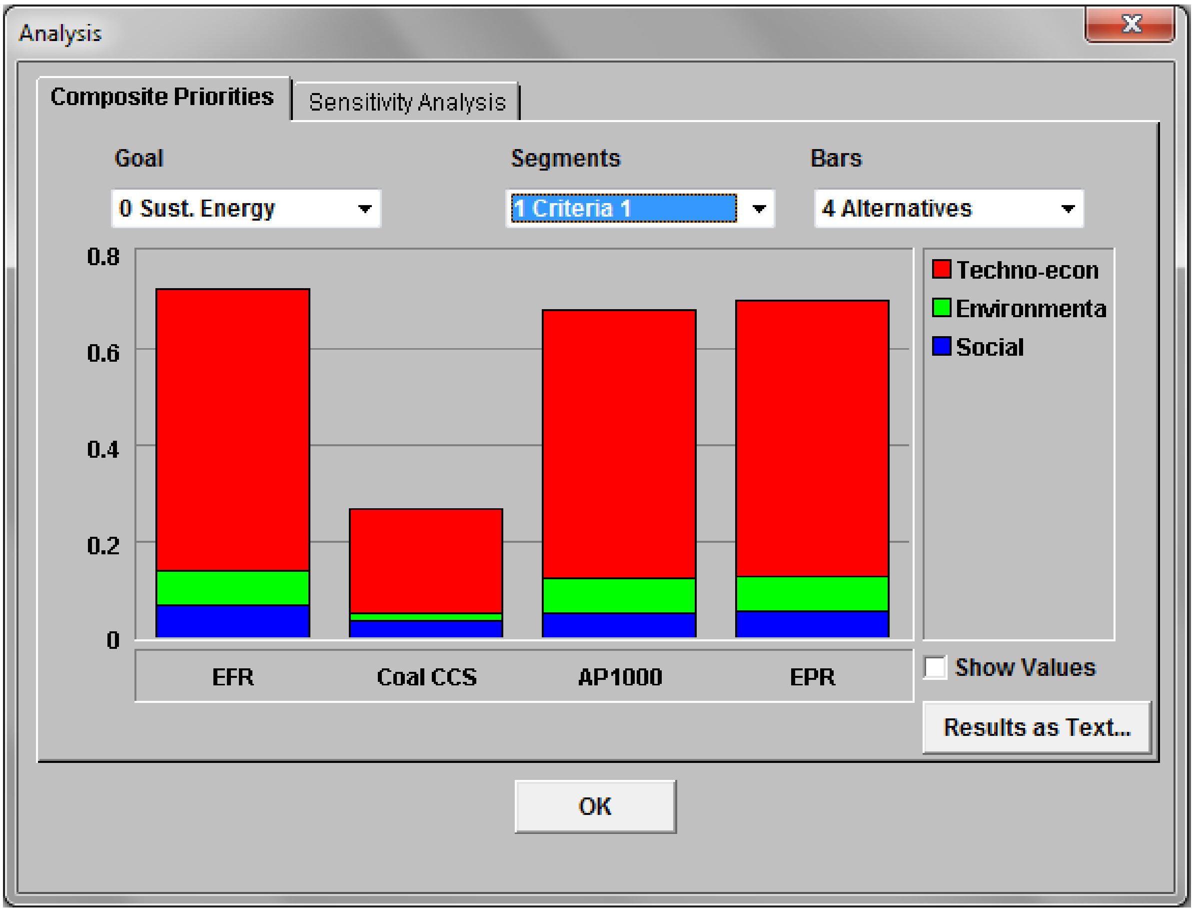
Goal
0 Sust. Energy

Segments
1 Criteria 1

Bars
4 Alternatives

Figure 7.59. Sustainability ranking of the four competing electricity options with equal weights on all indicators.

The same order of preference is found for all other cases considered, whereby the highest weighting is given to the techno-economic (Figure 7.60), environmental (Figure 7.61) and social (Figure 7.62) aspects. Therefore, the overall sustainability score appears not to be sensitive to the preferences for different sustainability criteria.



Goal: 0 Sust. Energy

Segments: 1 Criteria 1

Bars: 4 Alternatives

Figure 7.60. Sustainability ranking of the four competing electricity technologies with equal weighting placed on environmental and social indicators and a majority weight placed on the techno-economic indicators (with a weight of 0.8 placed on techno-economic aspects and weights of 0.09 placed on both the environmental and social aspects of sustainability).

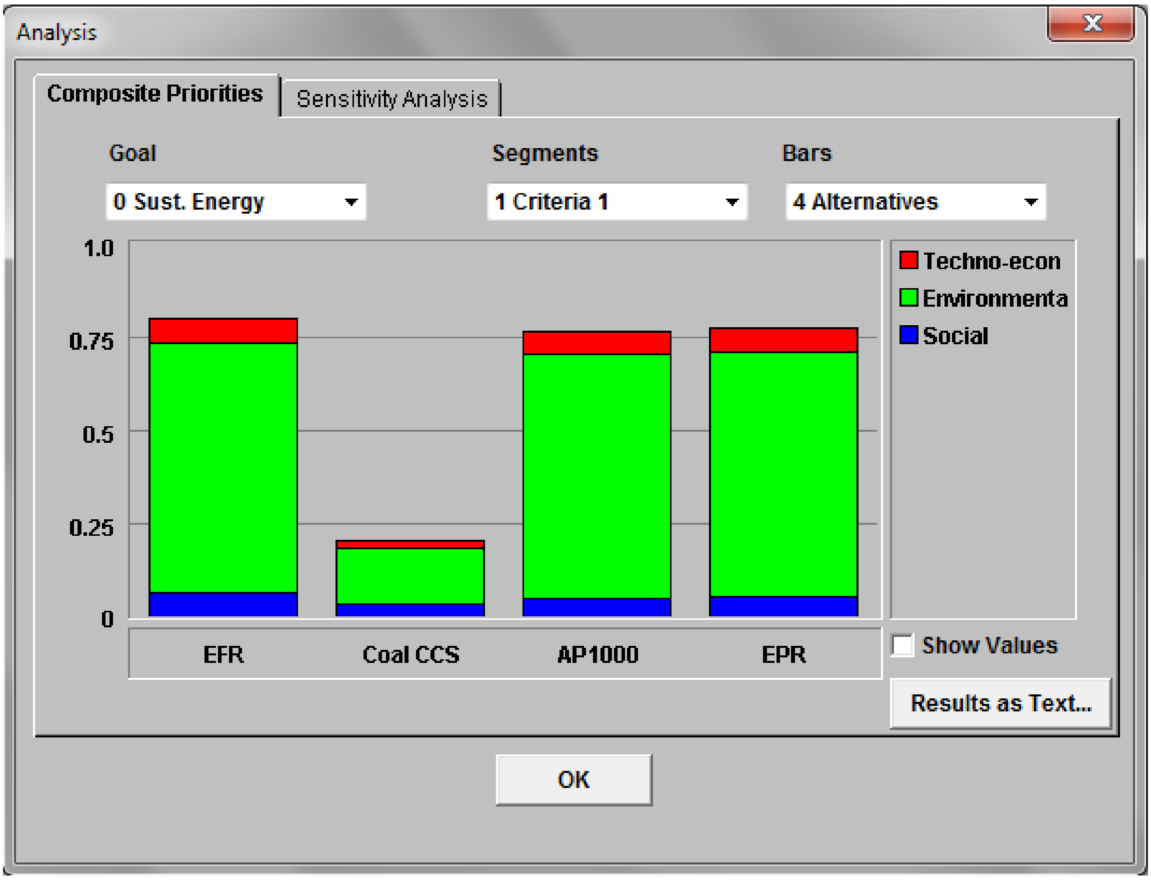
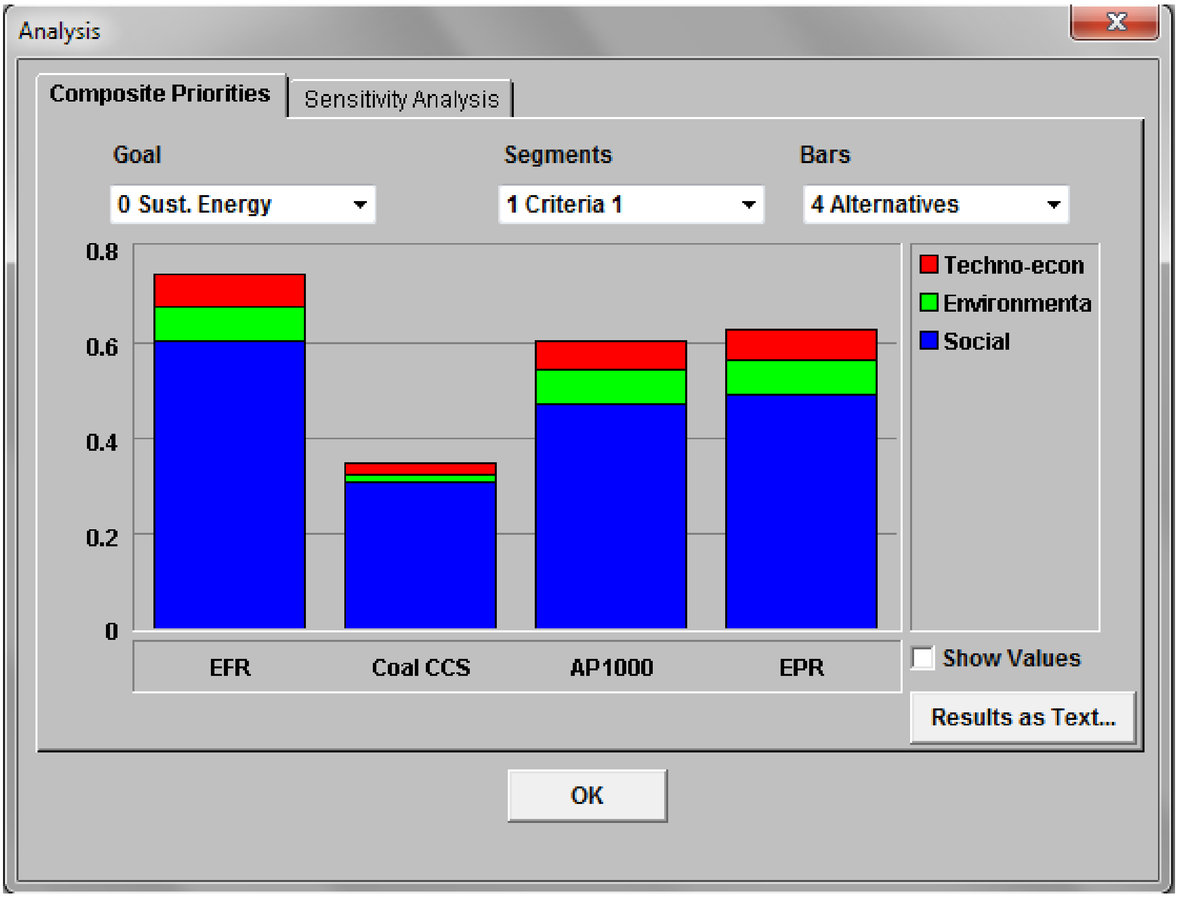


Figure 7.61. Sustainability ranking of the four competing electricity technologies with equal weighting placed on techno-economic and social indicators and a majority weight placed on the environmental indicators (with a weight of 0.8 placed on environmental aspects and weights of 0.09 placed on both the techno-economic and social aspects of sustainability).



Goal: 0 Sust. Energy

Segments: 1 Criteria 1

Bars: 4 Alternatives

Figure 7.62. Sustainability ranking of the four competing electricity technologies with equal weighting placed on environmental and techno-economic indicators and a majority weight placed on the social indicators (with a weight of 0.8 placed on social aspects and weights of 0.09 placed on both the environmental and techno-economic aspects of sustainability).

7.3 Summary

This chapter has evaluated the sustainability impacts of four possible future electricity-generating technologies for the UK: AP1000, EPR, EFR and coal CCS. The results suggest that EFR is the most and coal CCS the least sustainable option.

With respect to the greenhouse gas emissions, one of the main drivers for these new technologies, coal CCS has the highest GWP (296 g CO_2 eq./kWh). The best option is EFR with 1.4 g CO_2 eq./kWh, followed by the EPR (5.1 g CO_2 eq./kWh) and AP1000 (5.5 g CO_2 eq./kWh). However, the nuclear options contribute to a number of sustainability issues which coal CCS does not have, including, radioactive waste and nuclear proliferation.

The next chapter extends the analysis presented in this chapter to explore how the sustainability impacts change when different future electricity scenarios are considered, incorporating these and other electricity technologies.

8 Current UK Electricity Mix and Future Electricity Scenarios: Integrated Sustainability Assessment

This chapter presents the results of an integrated sustainability assessment of the current UK electricity mix and future electricity scenarios. The current UK electricity mix is described in section 8.1. The scenarios and their development are described in section 8.2. Section 8.3 presents the results of the integrated sustainability assessment of both the current electricity mix and future UK electricity scenarios considered in this work. In section 8.4, the different scenarios are compared using multi-criteria decision analysis. The conclusions are presented in section 8.5.

8.1 Current UK Electricity Mix

The current UK electricity mix is included in this analysis for comparison to future electricity scenarios. Current day technologies have not been modelled as part of this thesis, so data from Stamford and Azapagic (2012) is used in order to calculate the impacts of the present day electricity mix. The technologies considered as part of the current electricity mix include: coal-fired power; gas-fired power; nuclear power; offshore wind; and solar power. The specifications for these technologies are summarised in Table 8.1.

Table 8.1. Summary of technology types used for the current day electricity mix, taken from Stamford and Azapagic, 2012.

Technology Type	Technical Specification
Coal-fired power	Pulverised coal-fired power plant of 460 MW, 36% efficiency.
Gas-fired power	CCGT gas power plant of 400 MW capacity, 58% efficiency.
Nuclear power	PWR nuclear power plant of 1000 MW capacity, capacity factor of 85%, fuel burn-up of 53 GWd/tU
Wind Power	Offshore wind farm consisting of 3 MW wind turbines, capacity factor of 30%.
Solar power	Mixture of solar PV, consisting of 38.5% mono-crystalline Si, 52.3% multicrystalline Si, 4.7% amorphous Si, 2.9% ribbon Si and 1.6% CdTe and CIGS (cadmium-indium-gallium-selenide) Panels.

Although additional electricity technologies are comprised in the UK electricity mix, the sustainability data for these technologies are not currently available, and so the percentage penetration of the technologies is approximated to represent the UK's current electricity mix. Therefore, the current UK electricity mix is taken to be: gas-fired power (46.8%); coal-fired power (30.4%); nuclear power (20.1%); wind power (2.7%) and solar power (0.001%) (Stamford, 2012).

8.2 Development of Future UK Electricity Scenarios

The UK and many of the world's nations are rethinking their energy policy – energy security, climate change and the cost of energy provision are big drivers for energy policy development at home, and abroad. The global dependence on fossil fuels and a realisation that significant change is needed in order to provide energy security into the future, in addition to limiting the environmental damage that fossil fuels cause has led to global discussion on the future of energy provision and electricity generation. The most discussed driver for provision of low carbon energy is the effect that carbon emissions and other greenhouse gases have on anthropogenic climate change. In an attempt to meet these aims, energy scenario exploration is used here in order to investigate the impacts of a range of energy futures in the UK. Energy scenario development and analysis allows the constraints and drivers of energy policy development in the UK to be taken account of, and discussion and trade-offs of the potential impacts of various scenarios can then be made. Although energy scenario analysis allows long-term planning of energy systems, the scenarios are not predictions and only allow users to identify potential impacts of, barriers to and drivers for the range of scenarios explored.

As outlined in section 3.4, four scenarios are considered for this assessment. Scenario A is based on the UKERC 'Faint-heart' scenario (UKERC, 2009) where limited action takes place in order to limit climate change (carbon emissions are reduce 65% based on 1990 levels). Scenarios B and C are based on the UKERC 'Carbon ambition' scenario, where carbons emissions decrease in line with UK targets. Energy use is reduced and electricity generation is decarbonised by 2050. Scenario C differs from scenario B in that electricity use triples based on 2008 consumption. Scenario D displays a reduction in carbon emissions that (if replicated globally) would limit the chance of anthropogenic climate change temperature rise exceeding 2^{o}C.

Table 8.2. Technical specification of technologies and sources of data considered in the assessment of future electricity scenarios.

Technology Type	Technical Specification and Source	Scenario Year Considered
Coal-fired power	UK pulverised coal-fired power plant of 460 MW, 36% efficiency (Stamford and Azapagic, 2012).	2008
	Pulverised coal-fired power plant of 350 MW (data obtained from NEEDS (NEEDS, 2008).	2020
	Pulverised coal-fired power plant of 600 MW (data obtained from NEEDS (NEEDS, 2008).	2020; 2035
	Pulverised coal-fired power plant of 800 MW (data obtained from NEEDS [NEEDS, 2008]).	2020; 2035; 2050
	Coal IGCC 400 and 450 MW (data obtained from NEEDS [NEEDS, 2008]).	2020; 2035; 2050; 2070
	Coal CCS power (data used from section 7 of the thesis).	2020; 2035; 2050; 2070
	Coal CCS power: minimum and maximum values for IGCC, post-combustion and oxyfuel combustion (data obtained from NEEDS [NEEDS, 2008]).	2020; 2035; 2050; 2070
Gas-fired power	CCGT gas power plant of 400 MW capacity, 58% efficiency (Stamford and Azapagic, 2012).	2008
	CCGT gas power plant 500 MW (data obtained from NEEDS [NEEDS, 2008]).	2020; 2035; 2050; 2070
Nuclear power	PWR nuclear power plant of 1000 MW capacity, capacity factor of 85%, fuel burn-up of 53 GWd/tU (Stamford, 2012).	2008; 2020; 2035; 2050; 2070
	AP1000 nuclear power plant (data used from section 7 of the thesis).	2035; 2050; 2070
	EPR nuclear power plant (data used from section 7 of the thesis).	2035; 2050; 2070
	EFR, analysed in section 7 of the thesis (data obtained from NEEDS [NEEDS, 2008]).	2050; 2070
Wind Power	Offshore wind farm consisting of 2 MW wind turbines, capacity factor of 30 and 50% (Kouloumpis *et al.*, 2012).	2008; 2020; 2035
	Offshore wind farm consisting of 3 MW wind turbines, capacity factor of 30, 40 and 50% (Stamford, 2012).	2008; 2020; 2035; 2050; 2070
	Offshore wind farm consisting of 5 MW wind turbines, capacity factor of 30 and 50% (Stamford, 2012).	2008; 2020; 2035; 2050; 2070
Solar power	Mixture of solar PV (38.5% mono-crystalline Si, 52.3% multicrystalline Si, 4.7% amorphous Si, 2.9% ribbon Si and 1.6% CdTe and CIGS [cadmium-indium-gallium-selenide] panels) (Stamford, 2012).	2020; 2035; 2050
	Solar power plant in ground, minimum and maximum values (data obtained from NEEDS [NEEDS, 2008]).	2020; 2035; 2050; 2070

Each scenario shown in Table 8.3 - Table 8.6 displays the percentage penetration of each technology type, which is based on the ETLCA tool (Kouloumpis *et al.*, 2012), although the percentage contribution of each technology differs from the scenarios presented in the ETLCA tool in order to explore different electricity futures. The assumptions for the scenarios are summarised in Table 8.3., Table 8.4, Table 8.5 and Table 8.6. The technical specifications of the range of technologies considered for the scenario analysis are presented in Table 8.2. The LCA modelling is specific to these technologies. The techno-economic and the majority of the social indicator values (apart from the LCA values) are taken from Stamford (2012).

8.2.1 Scenario A

Table 8.3. summarises the assumptions for scenario A (Kouloumpis *et al.* (2012) in terms of: electricity consumed, change in electricity consumption relative to 2008, direct carbon emissions and change in carbon emissions relative to 2008.

In this scenario, which is based on the UKERC ‘Faint-heart’ scenario (UKERC, 2009), some action is taken to limit the impact of climate change and to reduce carbon emissions, but not enough to negate the extreme climatic events that may occur as a result of anthropogenic climate change. By 2050, direct carbon emissions from electricity are reduced 65% of 1990’s value, and by 2070 they are reduced by 80% of 1990’s value.

Table 8.3. Electricity mix for scenario A in the years 2020, 2035, 2050 and 2070 (Kouloumpis *et al.* (2012).

Scenario	Year	Electricity consumption (GWh)	Change in electricity consumption relative to today (2008) (%)	Direct carbon emissions (Mt C)	Carbon reduction relative to 1990 (%)	Electricity mix (technologies %)
A	2020	336 375	-11	39.32	32	Nuclear (11); coal (33); natural gas (53); offshore wind (3); solar (0); coal CCS (0)
	2035	376 729	1	34.42	41	Nuclear (16); coal (22); natural gas (47); offshore wind (3.5); solar (0); coal CCS (11.5)
	2050	407 855	9	20.53	65	Nuclear (33); coal (11); natural gas (27); offshore wind (6); solar (0); coal CCS (23)
	2070	455 539	18	11.85	80	Nuclear (38); coal (4); natural gas (14); offshore wind (17); solar (0); coal CCS (27)

The percentage penetration of various electricity-generating technologies are listed in Table 8.3 and displayed in Figure 8.1. The penetration of coal gradually decreases in line with carbon restrictions in this scenario. Generation of nuclear power, wind power (offshore) and coal CCS power are increased from the year 2035. Generation of power from natural gas also declines, but at a slower rate than coal-fired power. Solar power does not feature within this electricity scenario.

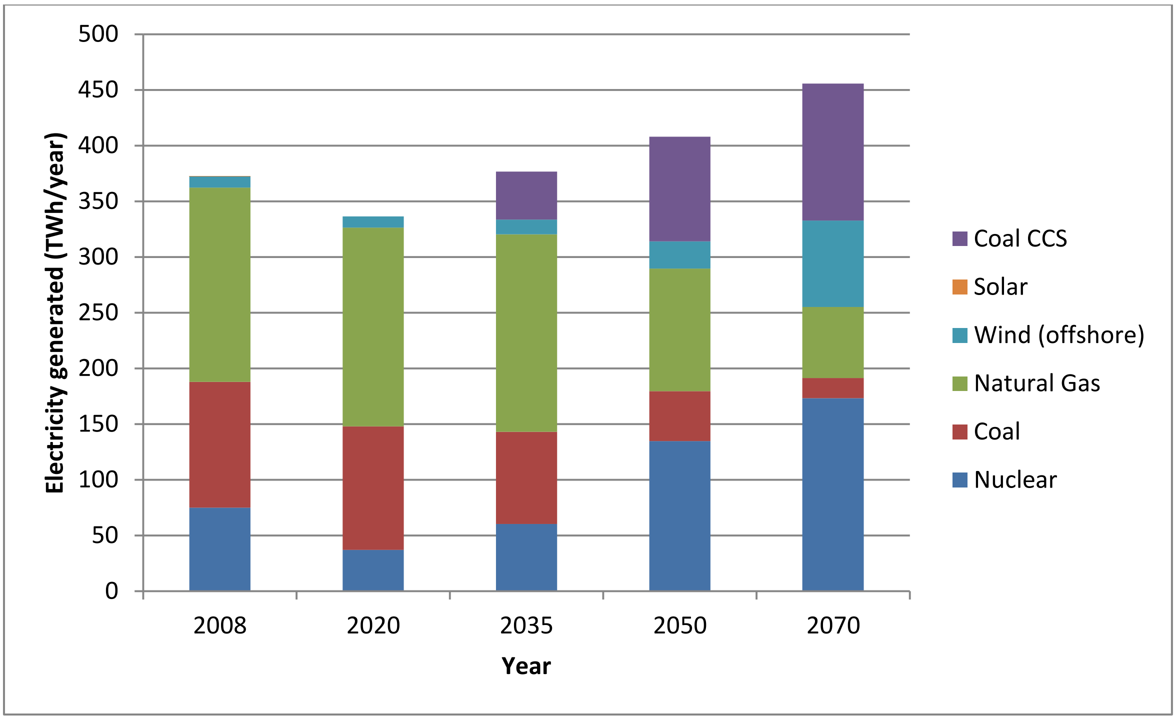


Figure 8.1. Amount of electricity generated by technology type under Scenario A in each assessment year.

8.2.2 Scenario B

Table 8.4 summarises the B scenario in terms of: electricity consumed, change in electricity consumption relative to 2008, direct carbon emissions and change in carbon emissions relative to 2008.

In this scenario, which is based on the UKERC 'Carbon ambition' scenario (UKERC, 2009), action is taken to limit the impact of climate change and to reduce carbon emissions, and the electricity system is completely decarbonised. By 2035, carbon emissions from electricity are reduced by 90% of 1990's value, and by 2050 they are reduced by 100% of 1990's value. Overall energy use is reduced, but electricity demand grows slightly. The percentage penetration of various electricity-generating technologies are listed in Table 8.4 and displayed graphically by future assessment year in Figure 8.2.

Table 8.4. Table showing the attributes and electricity mix of the B scenario in the years 2020, 2035, 2050 and 2070 (Kouloumpis *et al.* (2012).

Scenario	Year	Electricity consumption (GWh)	Change in electricity consumption relative to today (2008) (%)	Direct carbon emissions (Mt C)	Carbon reduction relative to 1990 (%)	Electricity mix (technologies %)
B	2020	352 339	-6	37.59	35	Nuclear (10); coal (26); natural gas (56); offshore wind (6); solar (2); coal CCS (0)
	2035	383 940	3	6.02	90	Nuclear (10); coal (3); natural gas (10); offshore wind (28); solar (36); coal CCS (13)
	2050	535 115	30	0.00	100	Nuclear (15); coal (0); natural gas (0); offshore wind (28); solar (40); coal CCS (17)
	2070	483 676	23	0.00	100	Nuclear (20); coal (0); natural gas (0); offshore wind (20); solar (40); coal CCS (20)

The penetration of coal decreases significantly in line with carbon restrictions in this scenario and by 2035 the use of coal is almost phased out. Generation of nuclear power increases at a slower rate than in scenario A, and generation is more than doubled from this source by 2070. Wind power (offshore) increases to 2050, where it constitutes 28% of all electricity generated. Generation from coal CCS power is increased from the year 2020 and plays a significant part in the UK's electricity mix from 2035 onwards. Generation of power from natural gas also declines, but at a slower rate than coal-fired power. Solar power features heavily within this electricity scenario, in 2035 it constitutes 36% of the electricity mix and this rises to 40% by 2050.

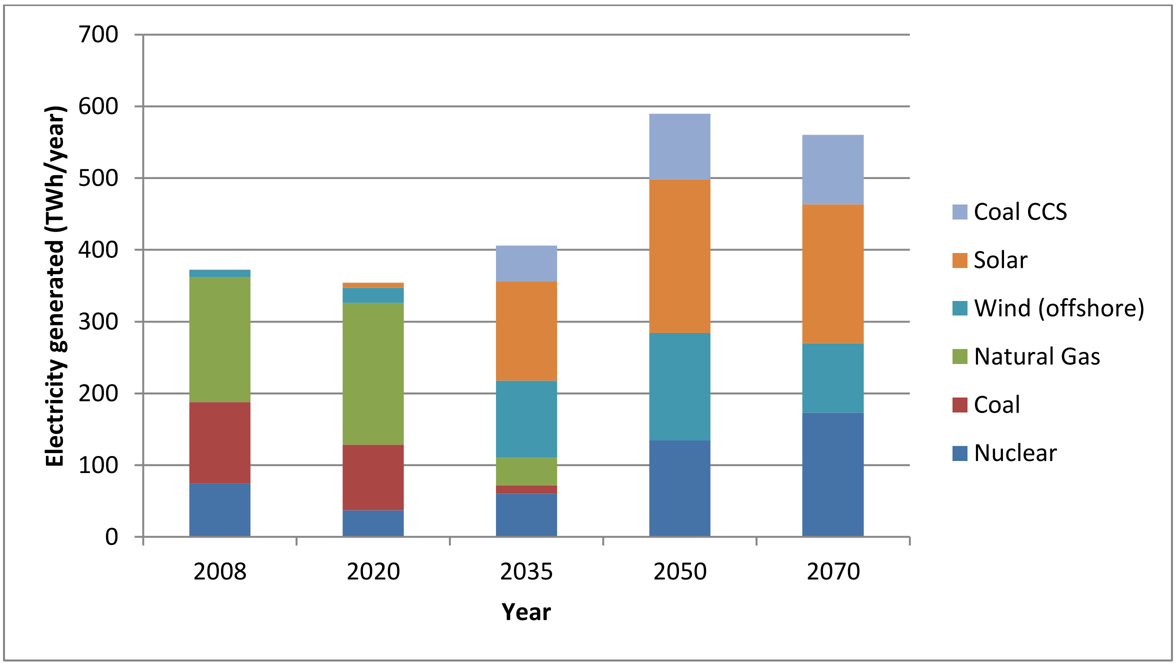


Figure 8.2. Amount of electricity generated by technology type under Scenario B in each assessment year.

8.2.3 Scenario C

Table 8.5 summarises the C scenario in terms of: electricity consumed, change in electricity consumption relative to 2008, direct carbon emissions and change in carbon emissions relative to 2008.

Table 8.5. Table showing the attributes and electricity mix of the C scenario in the years 2020, 2035, 2050 and 2070 (Kouloumpis *et al.* (2012).

Scenario	Year	Electricity consumption (GWh)	Change in electricity consumption relative to today (2008) (%)	Direct carbon emissions (Mt C)	Carbon reduction relative to 1990 (%)	Electricity mix (technologies %)
C	2020	409 738	9	36.91	36	Nuclear (9); coal (18.5); natural gas (50); offshore wind (6); solar (1.5); coal CCS (15)
	2035	891 011	58	18.92	67	Nuclear (30); coal (0); natural gas (14); offshore wind (15); solar (11); coal CCS (30)
	2050	1 099 819	66	0	100	Nuclear (30); coal (0); natural gas (0); offshore wind (45); solar (25); coal CCS (0)
	2070	1 189 303	69	0	100	Nuclear (26); coal (0); natural gas (0); offshore wind (48); solar (26); coal CCS (0)

In this scenario, which is based on the UKERC ‘Carbon ambition’ scenario (UKERC, 2009), which is the same action taken as in the B scenario, the impact of climate change is limited due to a significant reduction in carbon emissions, and the electricity system is completely decarbonised. By 2035, carbon emissions from electricity are reduced by 67% of 1990's value, and by 2050 they are reduced by 100% of 1990's value. Overall energy use is reduced, but electricity demand grows significantly and is tripled. The percentage penetration of various electricity-generating technologies are listed in Table 8.5 and displayed graphically by future assessment year in Figure 8.3. The penetration of coal decreases at a fast rate in line with carbon restrictions in this scenario and by 2020 the use of coal is almost phased out. Generation of nuclear power increases at a faster rate than in scenarios A and B, although its percentage penetration is lower than in scenario A. Wind power (offshore) has the highest penetration out of all technologies in this scenario, where it constitutes 48% of all electricity generated by 2070. Generation from coal CCS power is increased from the present day and constitutes 15% and 30% in the electricity mix in 2020 and 2035, respectively. Generation of power from natural gas also declines, at a slower rate than coal-fired power. Solar power again features heavily within this electricity scenario, where it is one of three majority electricity generation technologies. In 2050 it constitutes 25% of the electricity mix and this rises to 26% by 2070.

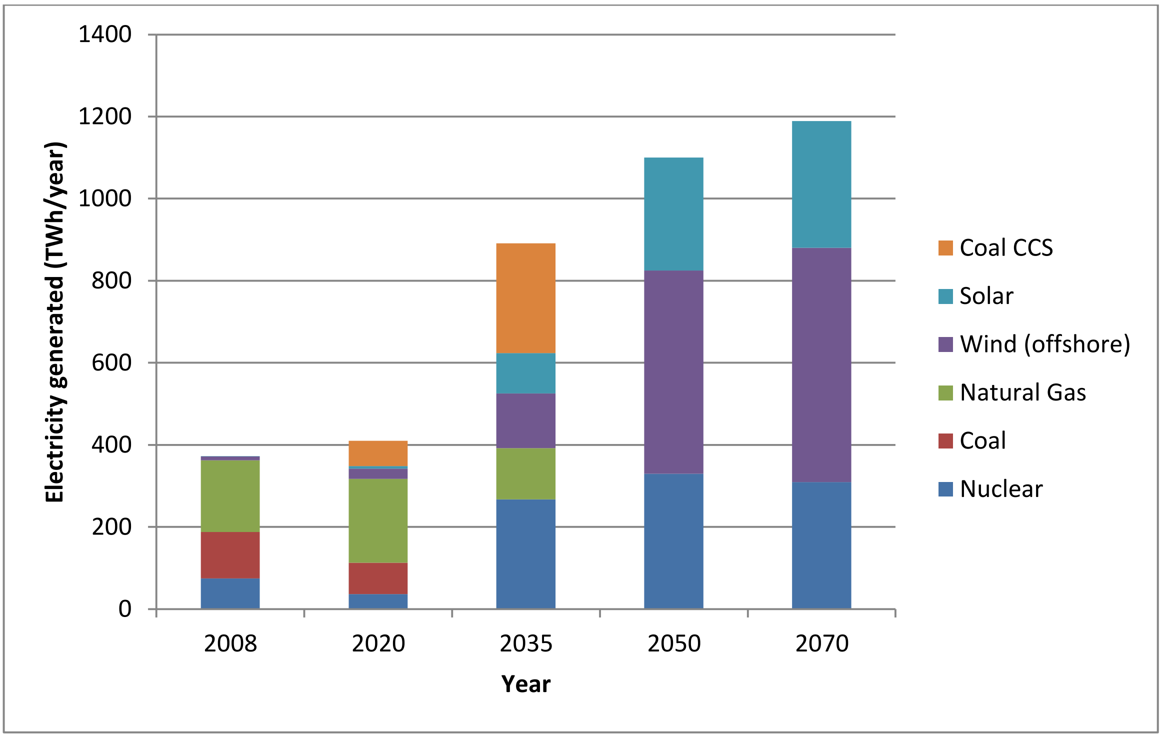


Figure 8.3. Amount of electricity generated by technology type under Scenario C in each assessment year.

8.2.4 Scenario D

Table 8.6 summarises the D scenario in terms of: electricity consumed, change in electricity consumption relative to 2008, direct carbon emissions and change in carbon emissions relative to 2008.

In this scenario, action is taken and carbon emissions are reduced at a rate that (if replicated globally), there would be a minimised chance of exceeding world average temperature rise of 2^{o}C, thus limiting the impact of 'dangerous' climate change. In this scenario, electricity use only increases moderately and this is completely decarbonised by 2025. In 2020 carbon emissions from electricity are reduced by 72% of 1990's value, and by 2035 they are reduced by 100% of 1990's value.

The percentage penetration of various electricity-generating technologies are listed in Table 8.6 and displayed graphically by future assessment year in Figure 8.4. The penetration of coal decreases at the fastest rate out of all the scenarios and is in line with carbon restrictions in this scenario. By 2020 the use of coal is phased out completely. Nuclear power generation is at its highest rate in this scenario and increases at a faster rate than in scenarios A, B and C. Its penetration reaches 59.5% in 2070. Scenario D is the only scenario in which nuclear power is generated from future generations of power stations, including the European Pressurised Reactor (50% of nuclear power in this scenario is generated by this method by 2070) and the European Fast Reactor (50% of nuclear power in this scenario is generated by this method in 2070). The rationale for this is that in this scenario, nuclear power dominated the UK's electricity mix, making it more likely than significant investment would have been made in nuclear power by the UK government and innovation to future reactors would be made. In the remaining scenarios, nuclear power is generated from the PWR (pressurised water reactor).

Table 8.6. Table showing the attributes and electricity mix of the D scenario in the years 2020, 2035, 2050 and 2070 (Kouloumpis *et al.* (2012).

Scenario	Year	Electricity consumption (GWh)	Change in electricity consumption relative to today (2008) (%)	Direct carbon emissions (Mt C)	Carbon reduction relative to 1990 (%)	Electricity mix (technologies %)
D	2020	408 772	9	16.08	72	Nuclear (19); coal (0); natural gas (36); offshore wind (25); solar (10); coal CCS (10)
	2035	499 428	25	0.00	100	Nuclear (52); coal (0); natural gas (0); offshore wind (33); solar (15); coal CCS (0)
	2050	455 233	18	0.00	100	Nuclear (56); coal (0); natural gas (0); offshore wind (36); solar (8); coal CCS (0)
	2070	389 221	4	0.00	100	Nuclear (59.5); coal (0); natural gas (0); offshore wind (39); solar (1.5); coal CCS (0)

Wind power (offshore) has the second highest penetration out of the technologies in this scenario, where it constitutes 39% of all electricity generated by 2070. Generation from coal CCS power is used in the short-term to bridge the gap to a low-carbon future and constitutes 10% of the electricity mix in 2020. Generation of power from natural gas plays a significant part of the electricity mix (36% in 2020) until after 2020, when it is phased out completely. Coal-fired power is also phased out, but before 2020, where coal CCS replaces some of the generation from coal-fired power. Solar power again features most significantly in the years between 2035 and 2050, where it constitutes 15% and 8% of the electricity mix, respectively.

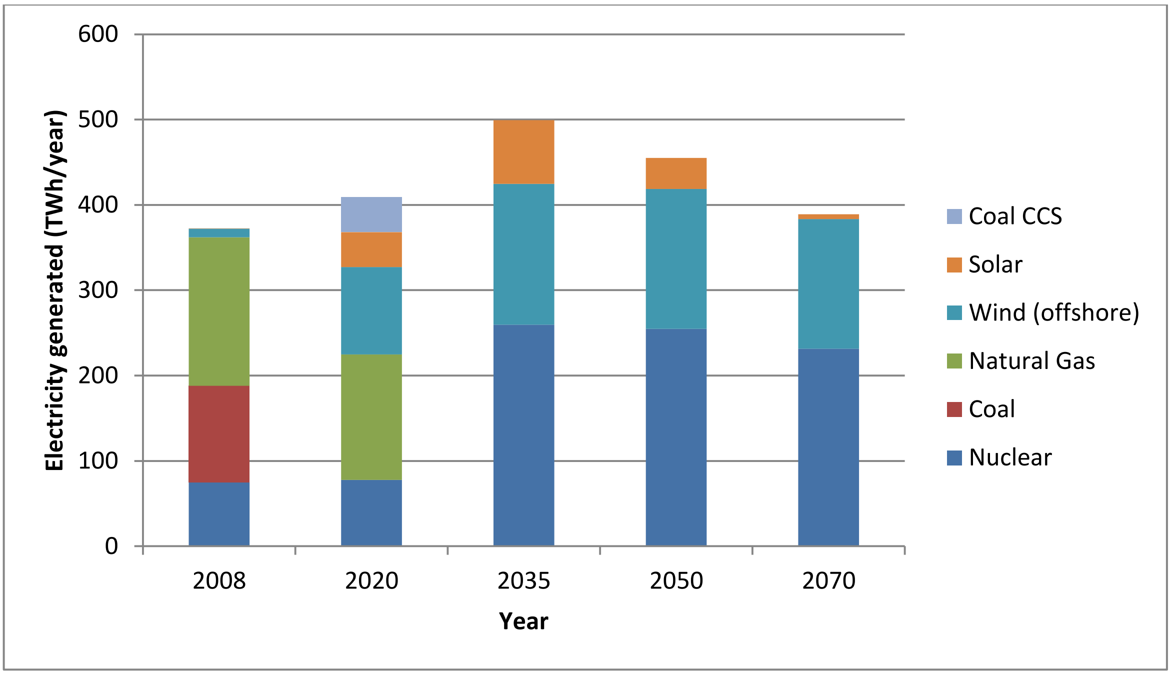


Figure 8.4. Amount of electricity generated by technology type under Scenario D in each assessment year.

8.2.5 Carbon emissions and global warming potential

The limits of direct CO_2 emissions for each family of scenarios are displayed in Figure 8.5. The potential pathways for CO_2 emissions reduction are shown for each scenario. In order to keep within the CO_2 constraint for any one of the scenarios, CO_2 emissions must not exceed the limits displayed. For comparison, the CO_2 emissions from the scenarios developed for analysis within this work are given in Figure 8.6.

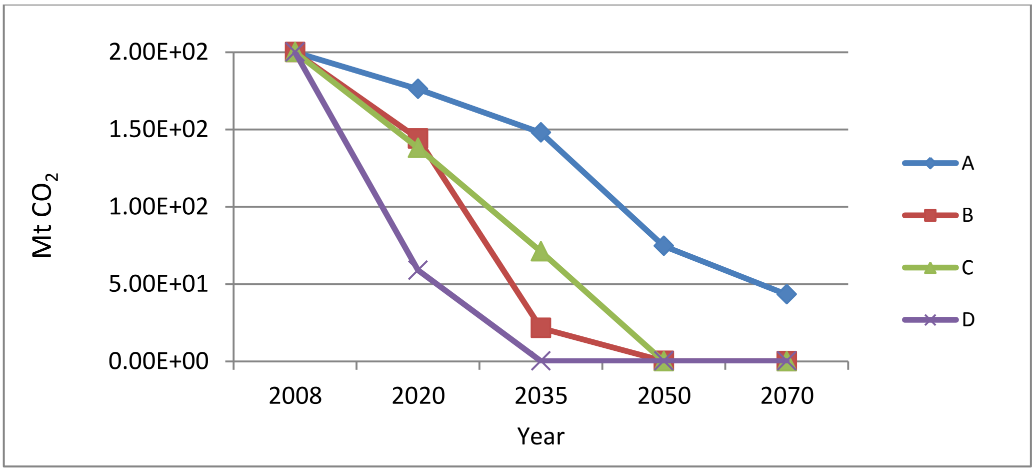


Figure 8.5. Limits on direct CO_2 emissions neede to meet the CO_2 constraints within each scenario.

From comparison of the suggested limits of CO_2 emissions and actual emissions from the chosen electricity mixes for the chosen scenarios, it can be seen that the pathways are broadly similar and display the same patterns of fall in emissions from present (2008) to 2070. The D scenario displays most similarity to the suggested limits for this scenario family. This is due to the low limits of emissions allowed under this scenario, therefore emissions allowed are used within each assessment year. Emissions from the developed A scenario fall more quickly than the trajectory in the permitted emissions graph. The permitted emissions of CO_2 are highest in this scenario, therefore the use of a relatively low-carbon electricity mix compared to the 2008 base year produce this trajectory. The B and C scenario emissions trajectories are also broadly similar to permitted CO_2 emissions.

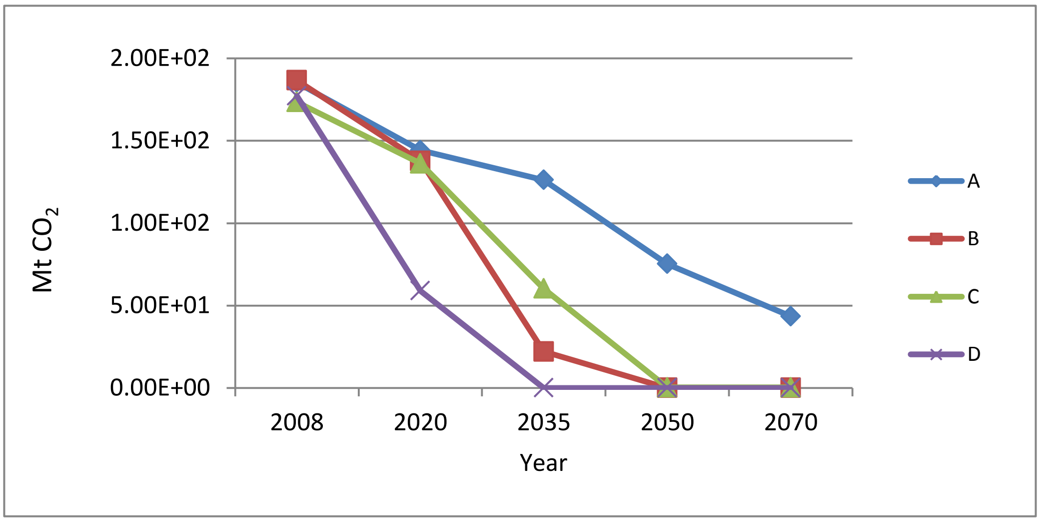


Figure 8.6. Actual direct emissions of CO_2 in each scenario.

Figure 8.7 shows the estimated GWP for each scenario, based on all greenhouse gas emissions and not only CO_2. These figures are based on the life cycle emissions of each electricity mix within each of the years assessed. The results of the GWP for the scenarios show that the impact of the electricity mixes on climate change is higher than is suggested by the emissions of direct CO_2 from these mixes; none of the scenarios has zero GWP. The scenario that has highest GWP impact is scenario A, followed by scenario C, then scenario B and finally, scenario D.

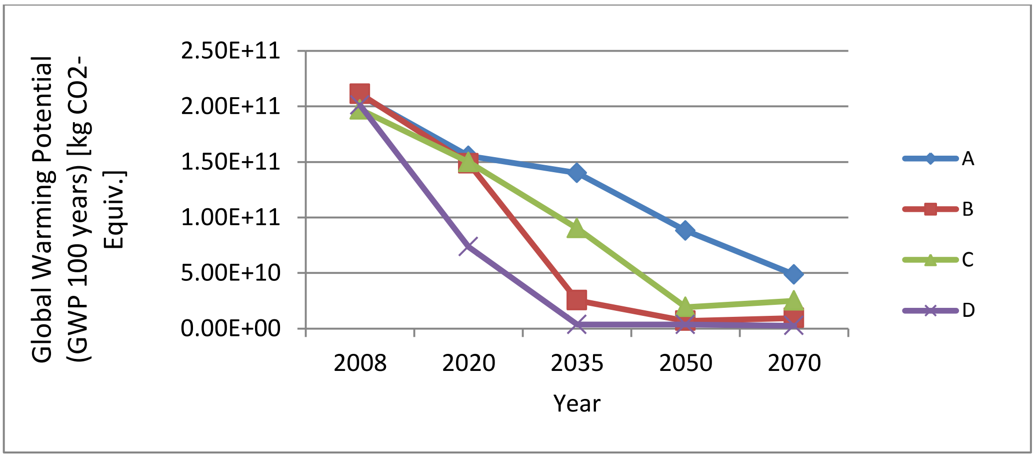


Figure 8.7. Global warming potential of the four scenarios.

8.3 An Integrated Sustainability Assessment of Current Electricity Mix and Future UK Electricity Scenarios

This section presents the results of the sustainability impacts of each of the electricity scenarios for the UK under each of the sustainability aspects using the SPRIng indicator framework to measure each aspect the indicators are those developed by Stamford and Azapagic (2012) and discussed previously in the dissertation. The data used to model the environmental impacts of the scenarios are taken from the SPRIng ETLCA tool (Kouloumpis *et al.*, 2012) and the data for the techno-economic and social impacts are taken from Stamford (2012). In addition, data calculated and approximated for the LCA impacts of the AP1000, European Pressurised Reactor and coal CCS power modelled within chapter 7 of this thesis are included. The results are presented for the year 2070 compared to the base year (2008); the full impacts for each assessment year (2020, 2035 and 2050) can be found in Appendix 11 – Appendix 13. Section 8.3.1 presents the results of the techno-economic impacts, section 8.3.2 presents the results of the environmental impacts, section 8.3.3 presents the results of the social impacts of the four scenarios.

8.3.1 Techno-economic sustainability

Figure 8.8 displays the results of the techno-economic impacts estimated in this work for each electricity scenario for the UK for the year 2070 compared to 2008 per unit of electricity generated.

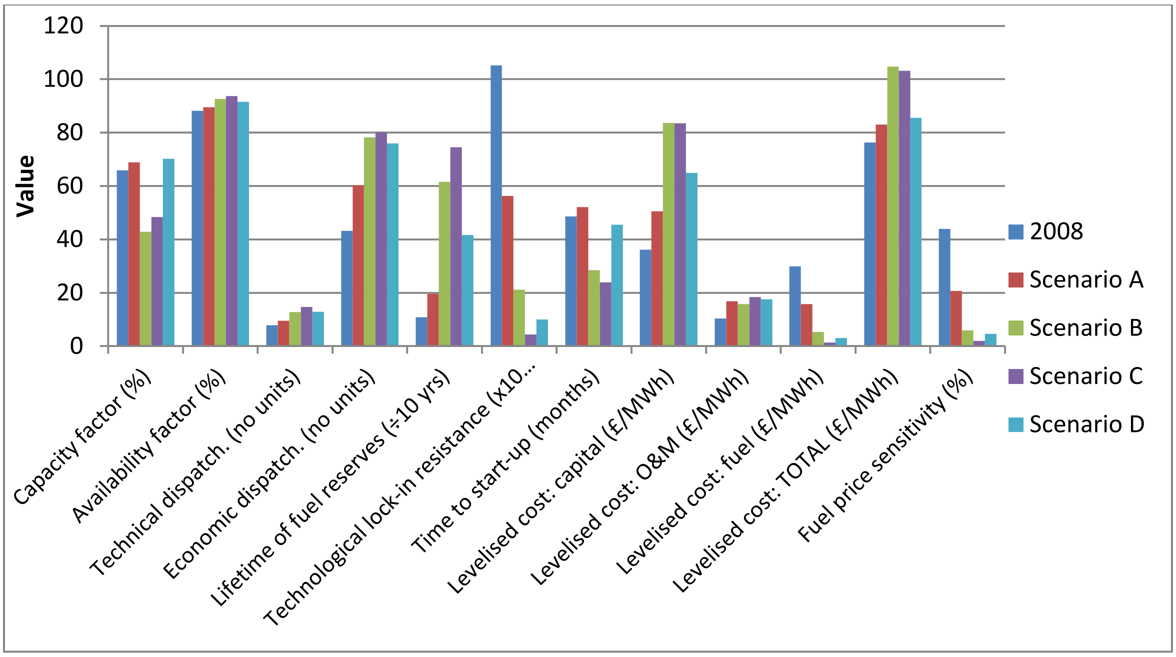


Figure 8.8. Techno-economic sustainability of the four future scenarios for the year 2070. For the indicators: capacity factor; availability factor; technological lock-in; and lifetime of fuel reserves, higher values are preferred. For the remainder of the indicators, lower values are preferred. [Where division and multiplication symbols are seen within the labels this means that the value of these indicators have either been divided or multiplied by the number specified in order to scale the value in line to other indicators on the graph.]

8.3.1.1 Operability

8.3.1.1.1 Capacity factor

The capacity factor is highest (70.2%) and most favourable under scenario D, and lowest (42.9%) and least favourable under scenario B. Scenario D manages to maintain a high capacity factor compared to the present day, which is around 66.9% due to the high penetration of nuclear power (59.5%) within this scenario. Scenario A also displays a high capacity factor (68.8%) also due to a relatively high penetration of nuclear power (38%). Conversely, scenarios B (42.9%) and C (48.3%) display relatively low capacity factors due to the high penetration of solar power in scenario B (40%) and wind power in scenario C (48%).

8.3.1.1.2 Availability factor

The availability factors of the competing scenarios are much less variable than the capacity factor. This is because the availability factors of the technologies assessed within these scenarios have relatively low variability compared to capacity factors. Nevertheless, the highest availability factor is displayed within scenario C (93.7%) and is closely followed by Scenario B (92.6%). This is due to the high availability of wind power and solar power, which exhibit availability factors of 95% and 96%, respectively. Compared to the present day availability (88.1%) all scenarios are more favourable.

8.3.1.1.3 Technical dispatchability

Scenario A has a technical dispatchability that is best (9.5) out of all scenarios and closest to the technical dispatchability of the present day, which is 7.8. Coal and coal CCS are the technologies which exhibit the most preferable technical dispatchability over other technologies. Therefore, the relatively high penetration of coal CCS in scenario A raises the technical dispatchability within this scenario. Scenarios C and B perform badly under this indicator (values of 12.7 and 14.6, respectively) due to the high proportions of offshore wind and solar power technologies, which display the worst technical dispatchability out of all the considered technologies.

8.3.1.1.4 Economic dispatchability

Economic dispatchability of the scenarios follows the same ranking as technical dispatchability, with scenario A performing well under this indicator (60.3) and scenario C performing badly (80.1), due again to the relatively high penetration of coal CCS power in scenario A and wind and solar power in scenario C. Compared to the present day (43.2), all future scenarios display less preferable economic dispatchability.

8.3.1.1.5 Lifetime of fuel reserves

Scenario C has the longest average lifetime of fuel reserves (745.2 years) out of all the scenarios based on the proportion penetration of the chosen technologies within this scenario. The dominant technologies (wind and solar power) raise the lifetime of fuel reserves above the other scenarios due to the lack of finite fuel needed for power generation from these sources. Conversely, scenario A performs relatively badly (196.3 years) under this measure due to the use of coal CCS and uranium fuel for use in thermal nuclear reactors. Compared to the present day value of 108.7 years, all scenarios are much more preferable than the current fuel mix for electricity generation.

8.3.1.2 Technological lock-in

Technological lock-in has the most preferable value in scenario A (5.6) and least preferable value in scenario C (0.4). Scenario A contains the highest proportion of coal CCS power out of all of the scenarios and coal CCS power performs the best out of all technologies with regard to lock-in due to its flexibility. Renewable technologies are inherently inflexible and therefore scenario C displays a much worse technological lock-in value due to the high penetration of solar and wind power. Compared to the present day technological lock-in measure (10.5) all future scenarios are less preferable.

8.3.1.3 Immediacy

Average time to start up of the electricity-generating technologies of the four scenarios is highest is scenario A (52 months) and lowest in scenario C (23.9 months). The present day immediacy value is around 48.6 months. Scenario A has a high time to start-up due to the relatively high proportion of nuclear power and also coal CCS power and gas-fired power which all have long start-up times (68, 61.6 and 37.5 months, respectively). Scenario C has the highest proportion of renewable technologies, which have the lowest start-up times – solar takes an average of 0.1 months to install and wind power has a start-up time of 12.8 months on average. Therefore, scenario C is the most preferred scenario under this measure and scenario A is the least preferred. The present day time to start up (48.6) is comparable to scenario D and therefore less preferable than most future electricity scenarios.

8.3.1.4 Levelised cost of generation

The cost of scenario A is the cheapest to implement (£83/MWh), and scenario B is the most expensive scenario to implement (£104.8/MWh), based on total costs. The present day cost of electricity generation is around £76/MWh. Therefore, all scenarios are more expensive to implement than the present day electricity mix. Scenario A contains the highest proportions of the least expensive technologies, including coal-fired power (4%), nuclear power (38%) and gas-fired power (14%). Scenario B contains the highest proportion of solar power out of all the scenarios, with 40% penetration. Solar power has total levelised costs of £123/MWh, which is more than double the cost of the cheapest technology to implement (coal-fired power is £61/MWh). Capital costs are also lowest in scenario A and highest in scenario B, due to the same reasons stated above regarding total levelised costs. Operation and maintenance costs are lowest within scenario B and highest in scenario C, this is due to the high penetration of solar power within scenario B, which has the second-lowest O&M costs out of all the technologies and due to scenario C having a high penetration of wind power, which has the highest O&M costs out of all the technologies considered. Fuel costs are lowest in scenario C as this scenario contains the highest proportion of renewables (solar and wind), which have no fuel costs. The highest fuel costs are within scenario A, which contains the highest amount of fuel-dependent electricity-generating technologies.

8.3.1.5 Cost variability

Scenario C is the least sensitive scenario, overall, to cost variability induced by sensitive fuel prices (with a fuel price sensitivity value of 2%). Scenario A is the most sensitive scenario to fuel price variability (20.7%). However, all scenarios display less sensitivity that the present electricity mix (43.9%). The low sensitivity in scenario C is due to the low dependence on fuel as the majority of this scenario is composed of solar (26%) and wind power (48%). Scenario A contains the most technologies dependent on supply of fuel for operation and is therefore the most sensitive to changes in fuel prices.

8.3.2 Environmental sustainability

Figure 8.9 and Figure 8.10 display the results of the environmental impacts estimated in this work for each electricity scenario for the year 2070, compared to the 2008 values, per unit of electricity generated.

8.3.2.1 Material recyclability

Figure 8.9 displays the results of the environmental impacts, ‘material recyclability’ and ‘land occupation’ of each electricity scenario developed for the UK for the year 2070 compared to the present day electricity mix (2008) per unit of electricity generated.

Material recyclability is highest in scenario C (0.95), and lowest in scenario A (0.86). Recyclability of materials is highest within the solar and wind power technologies, and as scenario C contains the highest proportion of the two technologies combined, this scenario displays the highest recyclability overall. The present day mix has one of the lowest recyclability proportions (0.86), which is almost exactly the same of that of scenario A.

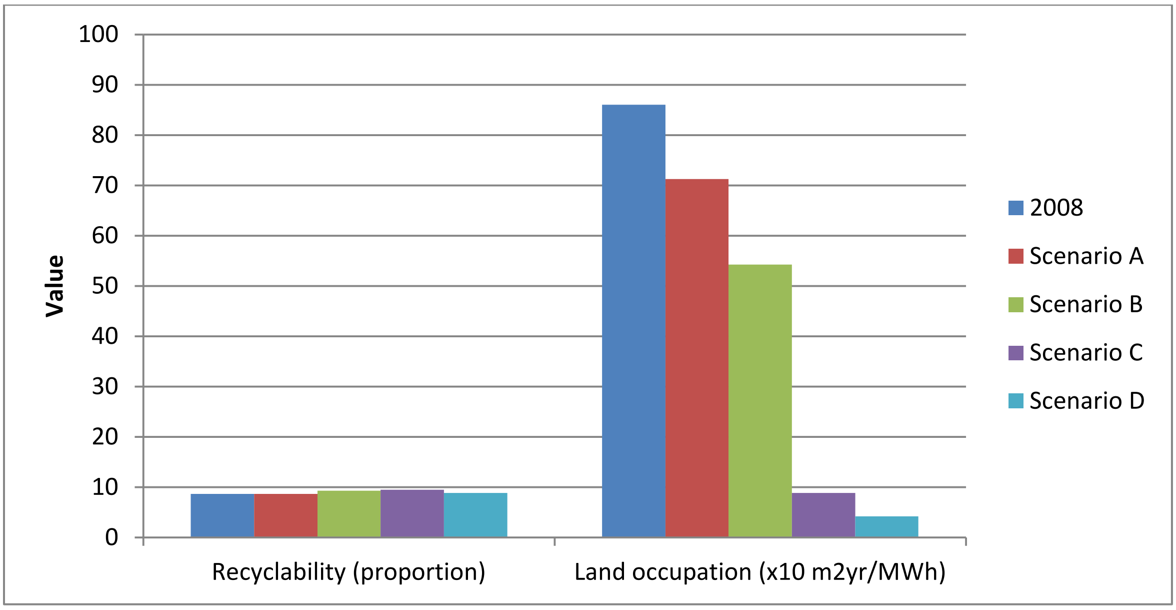


Figure 8.9. Performance of each of the four scenarios under the environmental indicators 'recyclability' and 'land occupation' for the year 2070. For 'recyclability', higher values are preferred, for 'land occupation', lower values are preferred. [Where division and multiplication symbols are seen within the labels this means that the value of these indicators have either been divided or multiplied by the number specified in order to scale the value in line to other indicators on the graph.]

8.3.2.2 Water eco-toxicity

8.3.2.2.1 <u>Freshwater aquatic eco-toxicity potential</u>

Freshwater aquatic eco-toxicity potential has the lowest impact in scenario A (1.34 x 10^{-2} kg DCB-equivalent), followed by scenario D (1.74 x 10^{-2} kg DCB-equivalent), and the highest impact in scenario B (2.41 x 10^{-2} kg DCB-equivalent), followed by scenario C (2.07 x 10^{-2} kg DCB-equivalent).

8.3.2.2.2 Marine aquatic eco-toxicity potential

The marine aquatic eco-toxicity impacts for 2008 and 2070 are displayed in Figure 8.10. Marine aquatic eco-toxicity potential has the lowest impact in scenario D (3.48×10^1 kg DCB-equivalent), followed by scenario C (5.15×10^1 kg DCB-equivalent), and the highest impact in scenario B (1.4×10^2 kg DCB-equivalent), followed by scenario A (1.38×10^2 kg DCB-equivalent). Compared to the present day value of 3.71×10^2 kg DCB-equivalent, all future scenarios are more preferable to the current electricity mix. The primary reason for the high freshwater eco-toxicity of the current electricity mix is the use of coal-fired power, which has the highest impact per kWh of electricity generation, compared to other electricity options.

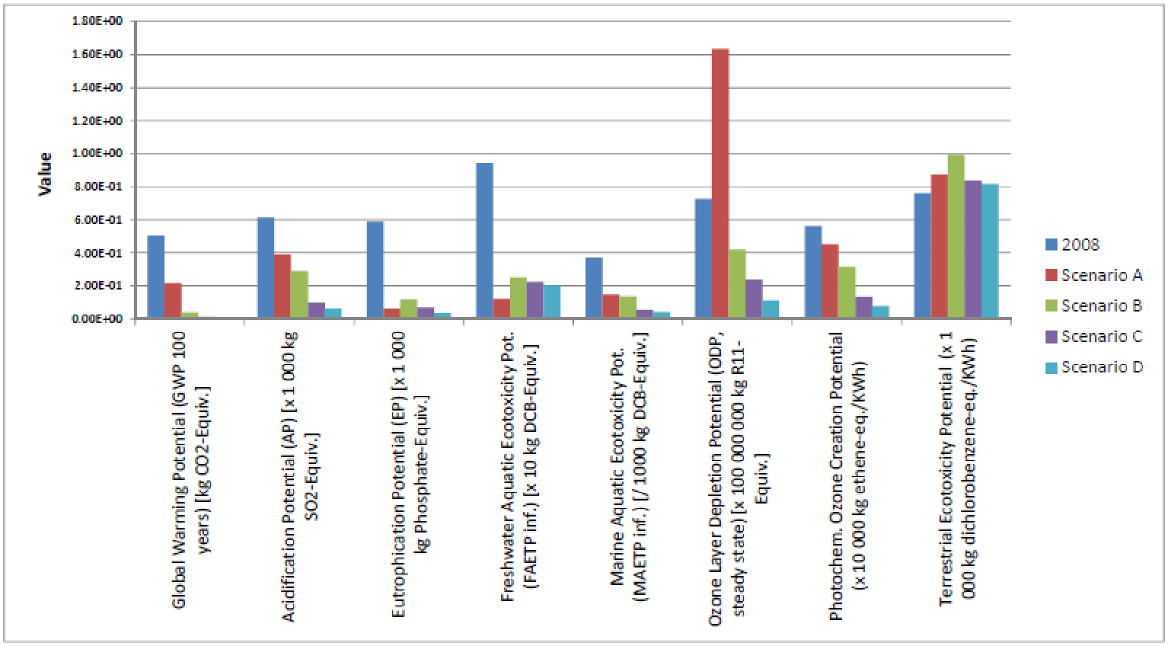


Figure 8.10. Performance of each of the four scenarios and the current electricity mix under the environmental indicators (except for land use and recyclability) for the year 2070. For all impacts, lower values are preferred. [Where division and multiplication symbols are seen within the labels this means that the value of these indicators have either been divided or multiplied by the number specified in order to scale the value in line to other indicators on the graph.]

8.3.2.3 Global warming potential

In 2070, the scenario that has the lowest GWP is scenario D (6.54×10^{-3} kg CO_2-equivalent). This is because the carbon constraints of scenario D are the most stringent and therefore low carbon technologies (nuclear, offshore wind and solar power) are used.

Figure 8.11. displays the GWP impacts of all scenarios from the base year (2008) to 2070. In the year 2070, scenario D has a total GWP of 1.68 x 10^9 kg CO_2-equivalent. Scenario B has the next lowest GWP, with a value of 1.8 x 10^{10} kg CO_2-equivalent. Scenario C has a similar GWP to scenario B, with a value of 1.85 x 10^{10} kg CO_2-equivalent and scenario A has the highest GWP value, at 4.87 x 10^{10} kg CO_2-equivalent.

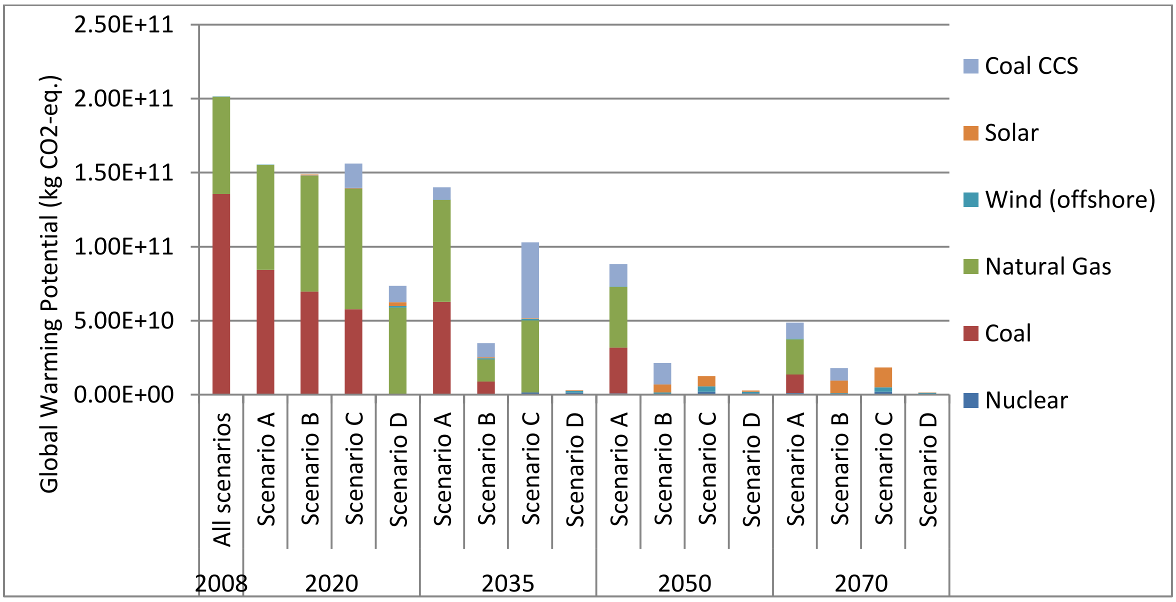


Figure 8.11. Total GWP impacts per year for the four developed scenarios in each assessment year.

8.3.2.4 Ozone layer depletion potential

The ozone layer depletion potential impacts for 2008 and 2070 are displayed in Figure 8.10. In 2070, scenario D displays the lowest ODP (5.54 x 10^{-10} kg R11-equivalent), followed by scenario C (2.27 x 10^{-9} kg R11-equivalent), then scenario B (3.94 x 10^{-9} kg R11-equivalent), and finally, scenario A has the highest ODP (9.03 x 10^{-9} kg R11-equivalent). The high values of ODP in scenario A are produced primarily by the use of fossil fuel technologies. All scenarios are more preferable to the present day situation (7.28 x 10^{-9} kg R11-equivalent) apart from scenario A, which displays a slightly higher value than the 2008 electricity mix.

8.3.2.5 Acidification potential

The highest acidification potential in the 2070 scenarios is in scenario A (2.6 x 10^{-4} kg SO_2-equivalent), followed by scenario B (2.42 x 10^{-4} kg SO_2-equivalent), then C (9.2 x 10^{-5} kg SO_2-equivalent), and finally, scenario D has the lowest AP (4.53 x 10^{-5} kg SO_2-equivalent). Again, the high impact of AC in scenario A is due to the use of fossile fuel (coal and natural gas) technologies. All he future scenarios are more preferable than the present day vale for AP of 6.14 x 10^{-4} kg SO_2-equivalent.

8.3.2.6 Eutrophication potential

In 2070, scenario D displays the lowest EP (2.32 x 10^{-5} kg phosphate-equivalent), followed by scenario A (4.28 x 10^{-5} kg phosphate-equivalent), then scenario D (6.57 x 10^{-5} kg phosphate-equivalent), and finally, scenario B has the highest EP (1.01 x 10^{-4} kg phosphate-equivalent). The present day electricity mix has the highest EP value out of all electricity mix options (5.88 x 10^{-4} kg phosphate-equivalent). The high EP of scenario B is primarily due to the high penetration of solar power, which comprises 40% of scenario B’s electricity supply in 2070 and has a relatively high EP per kWh compared to other low carbon electricity options.

8.3.2.7 Photochemical ozone creation potential

The photochemical ozone creation potential impacts for 2008 and 2070 are displayed in Figure 8.10. In the 2070 scenarios, scenario D has a very low POCP (5.12 x 10^{-6} kg ethane-equivalent) compared to the other scenarios (A, B and C) developed for this work, with respective values of 3.25 x 10^{-5} kg, 3.01 x 10^{-5} kg, and 1.28 x 10^{-5} kg ethane-equivalent. The low impact within scenario D is due to the high penetration of nuclear and offshore wind technologies, which display the lowest POCP impacts per kWh electricity produced (2.97 x 10^{-6} and 6.42 x 10^{-6} kg ethane-equivalent, respectively) compared to all the other electricity options. All scenarios are preferable to the present day POCP of 5.62 x 10^{-5} kg ethane-equivalent.

8.3.2.8 Land use and quality

8.3.2.8.1 Land occupation

Displayed in Figure 8.9 are the scenario impacts on land occupation. Scenario D is the most preferred scenario under this indicator (0.004 m^2yr/kWh), followed by scenario C (0.0089 m^2yr/kWh), then scenario B (0.054 m^2yr/kWh), and finally, scenario A (0.071 m^2yr/kWh) is the least preferred scenario. Compared to the present day electricity mix land occupation (0.086 m^2yr/kWh), all future scenarios are more preferable. Scenario D is comprised of a large amount of nuclear power and wind power technologies, which have relatively low land occupation values out of the technologies considered (offshore wind power has the lowest land use intensity out of all technologies at 1.6 x 10^4 m^2yr/kWh) and nuclear power is the third least intensive land use technology, with land use values of 5.4 x 10^4 m^2yr/kWh. Scenario A contains a higher proportion of land intensive technologies, such as coal CCS power (27% penetration at 2.1 x 10^2 m^2yr/kWh) and coal-fired power (4% penetration at 2.7 x 10^2 m^2yr/kWh).

8.3.2.8.2 Terrestrial eco-toxicity potential

The terrestrial eco-toxicity impacts for 2008 and 2070 are displayed in Figure 8.10. In 2070, scenario C has the lowest terrestrial eco-toxicity potential (7.46 x 10^{-4} kg dichlorobenzene-equivalent) and scenario B has the highest terrestrial eco-toxicity potential (9.08 x 10^{-4} kg dichlorobenzene-equivalent). The low TEP of scenario C is explained by the absence of coal CCS technologies, which contribute to TEP significantly in scenarios A and B. Scenario A and B display higher TEP than the present day situation (7.6 x 10^{-4} kg dichlorobenzene-equivalent) which is again due to the presence of coal CCS technologies within these scenarios.

8.3.3 Social sustainability

Figure 8.12 displays the results of the social impacts of each electricity scenario developed for the UK for the year 2070 per unit of electricity generated.

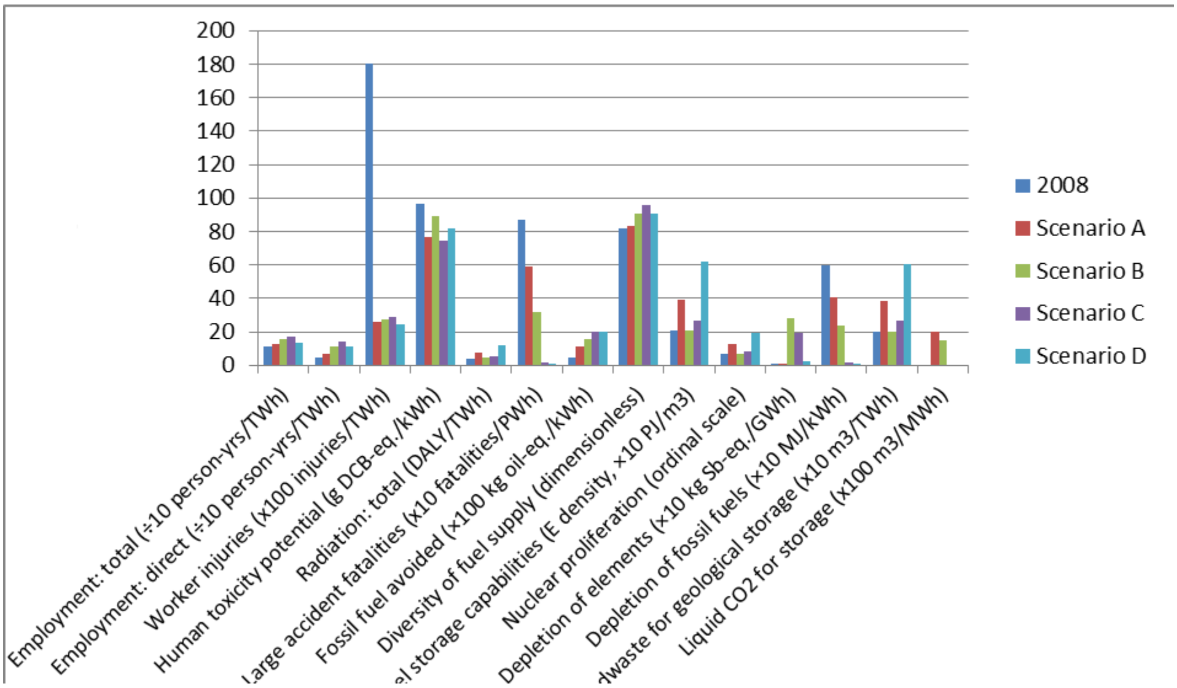


Figure 8.12. Performance of the 2008 electricity mix and each of the four scenarios under the social indicators for the year 2070. For the indicators: employment; fossil fuel avoided; diversity of fuel supply; and fuel storage capabilities, higher values are preferred, for the remainder of the indicators, lower values are preferred. [Where division and multiplication symbols are seen within the labels this means that the value of these indicators have either been divided or multiplied by the number specified in order to scale the value in line to other indicators on the graph.]

8.3.3.1 Provision of employment

Total employment displays greater values under scenario C (17 person-yrs/TWh), followed by scenarios B (15.9), D (13.8) and finally, scenario A displays the lowest value in total employment (13). Direct employment displays the same pattern. Scenario C displays the highest total and direct employment due to the high proportion of renewable technologies within this scenario, which demand high levels of employment per unit of electricity generated compared to other electricity options. Conversely, scenario A has the least penetration of renewable technologies and also a relatively high proportion of nuclear power, which has the second-lowest employment rates (compared to gas-fired power). All future scenarios display more preferable total employment to the present day situation (11.4 person-tys/TWh).

8.3.3.2 Human health impacts

8.3.3.2.1 Human health impacts from toxic substances

Human toxicity potential is highest in scenario B (88.8 g DCB-eq./kWh), making this scenario the least preferred option under this indicator, and lowest in scenario A (76.4 g DCB-eq./kWh), making this scenario the most preferred option under this indicator. A high proportion of solar power (40%) in scenario B, which has the highest HTP out of all the considered technologies determines this result. Scenario A has a variety of low HTP electricity options which comprise 58% of electricity generation within this scenario. All future scenarios display a more preferable HTP compared to the present day value of 96.8 g DCB-eq./kWh.

8.3.3.2.2 Human health impacts from radiation

Human health impacts from radiation have their highest impacts in scenarios D and A respectively, which contain the highest proportions of nuclear power, at 59.5% and 38%, which significantly contributes to the impact. Scenario B, which has the lowest proportion of nuclear power (20%) also has the lowest health impacts from radiation (4.3 g DCB-eq./kWh). The present day health impact from radiation is lower than any of the scenarios at 4.2 g DCB-eq./kWh (and a nuclear power penetration of 20%).

8.3.3.3 Large accident fatalities

Large accident fatalities has a high impact in scenario A (5.9 fatalities/PWh), followed by scenario B (3.21 g fatalities/PWh), which both dominate over the much smaller values in scenarios C and D (0.15 and 0.12 fatalities/PWh, respectively). The high accident rate in scenario A is due to the highest proportions of coal-fired power and coal CCS power within this scenario, which both have the highest impacts out of all the technologies considered, under this measure. Nuclear power has the lowest rate of large accident fatalities, and the high proportion of nuclear power in scenario D minimises this impact in this scenario. All scenarios display lower values for large accident fatalities than the present day situation (8.7 fatalities/PWh). The immaturity of offshore wind and solar power in the present contribute to this value, as it is assumed that as these technologies become more mature, health and safety practices will become more stringent from the learning curve experienced when any new technology is implemented (Stamford, 2012).

8.3.3.4 Energy security

8.3.3.4.1 Amount of fossil fuel potentially avoided

The amount of fossil fuel avoided per kWh of electricity produced is highest in scenarios C and D (20.01 kg oil-eq./kWh) which both contain 0% penetration of fossil fuel technologies. Scenario A has the highest proportion of fossil fuel technologies within its electricity mix and therefore, the lowest fossil fuel avoided (11 kg oil-eq./kWh). Scenario B displays a value of 16 kg oil-eq./kWh. All technologies perform much better under this measure than the current situation; 2008 has a fossil fuel avoided value of 4.6 kg oil-eq./kWh due to the high proportion of fossil fuel technologies currently used (30.4% coal and 46.8% natural gas).

8.3.3.4.2 Diversity of fuel supply

This measure is based on current day imports of fuel extrapolated into the future. There is no way of predicting where future fuel supply will be imported from – this depends on many factors, including geopolitical relations, discovery of new fuel reserves, uptake of technologies around the world, etc. However, if fuel import diversity remains similar to today, the most diverse fuel supply mix is found within scenario C (95.8), followed by scenario B (90.9), then D (90.5) and finally, A (83). Scenario C contains the highest proportion of renewable technologies, which perform well under this measure due to the lack of fuel imports needed for electricity generation from these technologies. Scenario A performs worst under this indicator due to the dependence on coal imports, which has the least diverse supply mix out of all considered technologies. All of the future scenarios display a greater diversity of fuel supply than the present day (81.8) due to the current comparatively high reliance on fossil fuels.

8.3.3.4.3 Fuel storage capability

The highest fuel storage capability is found within scenario D of those considered (61.7 PJ/m^3), followed by scenario A (39.4 PJ/m^3). Scenario D's high fuel storage capability is attributable to the high proportion of nuclear fuels used in this scenario, which are very energy dense. Scenario A is also comprised of a high proportion of nuclear power (38%). Conversely, scenario B performs badly under this indicator (20.7 PJ/m^3) due to the higher proportion of renewable technologies, of which fuel cannot be stored, combined with the lowest proportion of nuclear power out of all the considered scenarios. Scenario C displays a similar fuel storage capability to scenario B (27 PJ/m^3) for the same reasons. The current day fuel storage capability is valued at 20.8 PJ/m^3. This is also relatively poor compared to scenarios D and A and is due to the high proportion of gas-fired power (natural gas is not stored for power generation and therefore is very sensitive to delays in supply).

8.3.3.5 Nuclear proliferation

Nuclear proliferation affects all of the scenarios as each contains some proportion of nuclear power. This measure obviously has the highest impact (19.6) in the scenario with the highest proportion of nuclear power, which is scenario D (59.5%), followed bythe impact of scenario A (12.5), which contains 38% nuclear power.

8.3.3.6 Intergenerational equity

8.3.3.6.1 Abiotic depletion – elements

Implementation of scenarios B and C would cause the largest depletion of elements 28.4 and 19.5 kg Sb-eq./GWh, respectively, due to the highest proportions of solar and wind power found within these scenarios. Solar and wind power are both elementally intense technologies. Conversely, nuclear, coal- and gas-fired power are elementally much less intense, meaning than scenario A is the most preferred option (with a value of 1.2 kg Sb-eq./GWh) under this measure. Scenario D also displays a low value of 2.5 kg Sb-eq./GWh. The present day abiotic depletion is 0.6 kg Sb-eq./GWh, meaning that the current day situation is the most preferred under this measure.

8.3.3.6.2 Abiotic depletion – fossil fuels

Fossil fuels are at their highest depletion rates within scenario A (41 MJ/kWh), followed by scenario B (23.5 MJ/kWh), which have the highest proportions of fossil fuel technologies. Scenario A is composed of 45% fossil fuel technologies and scenario B is composed of 20% fossil fuel technologies. However, the current day situation has the highest fossil fuel depletion impact of 60.1 MJ/kWh. Scenarios C and D have the lowest impacts, with values of 2 and 0.8 MJ/kWh, respectively, due the absence of fossil fuel technologies.

8.3.3.6.3 Radioactive waste to be stored

Radioactive waste storage is at its highest amount (6 and 3.9 m^3/TWh) within the scenarios that contain the highest penetration of nuclear power – scenarios D (60%) and A (38%). The present day situation and scenario B display the lowest levels of radioactive waste to be stored (2.04 and 2.03 m3/TWh, respectively).

8.3.3.6.4 Volume of CO_2 to be stored

CO_2 sequestration is only needed in scenarios A and B (0.2 and 0.15 m^3/MWh) which have 27% and 20% penetration of coal CCS power, respectively.

8.4 Multi-Criteria Analysis of Future UK Electricity Scenarios

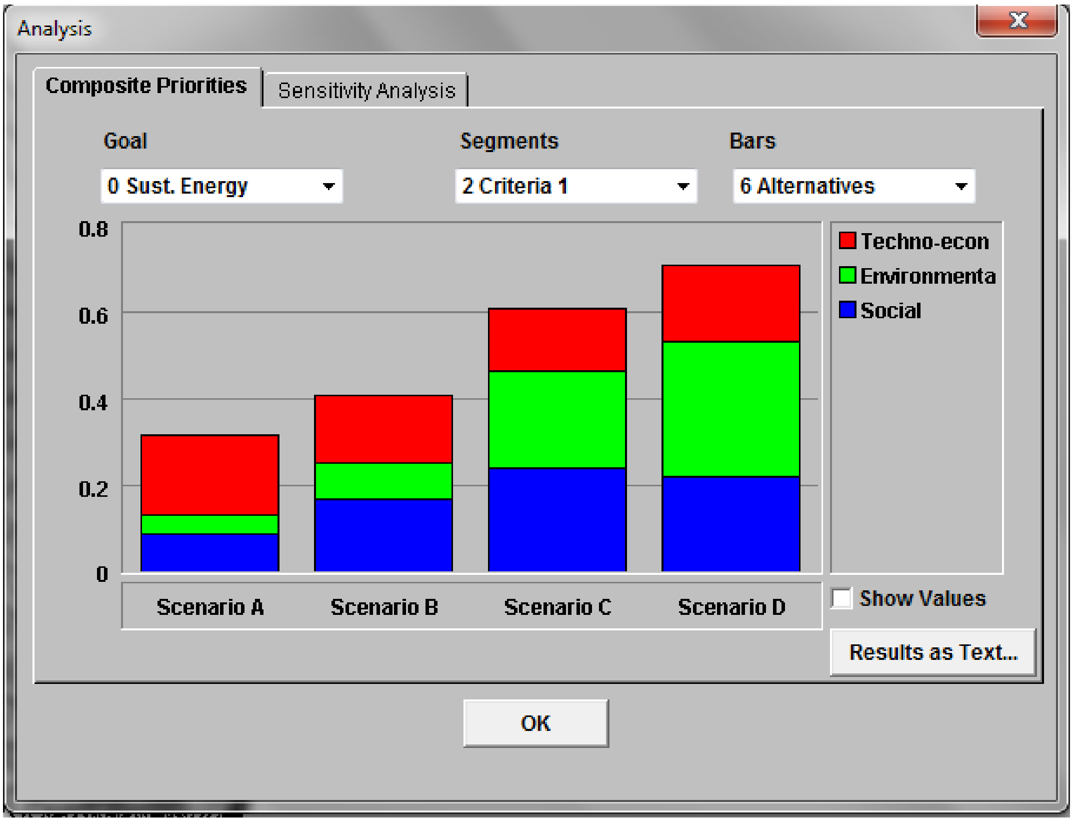
This section considers the sustainability impacts of the four scenarios using MCDA. Expert and public stakeholder preferences for different technologies, identified in Chapters 4 and 5, are placed on the indicators to determine the ‘most sustainable’ future electricity scenario of those considered here.

The method for weight derivation varies across the indicators, electricity technologies and sustainability aspects. For the electricity technologies, a simple ranking method was used. For the sustainability indicators, the SWING method was used and for the sustainability aspects, the AHP method was used (see Chapter 2 for the methodology). The reason for this variation in MCDA method relates to the number of criteria being assessed against each other. The AHP method is a valuable tool to use when comparing a small number of criteria – stakeholders make pairwise comparisons across all of the criteria, allowing them to concentrate on two criteria at a time and make reasoned decisions. However, as the number of criteria increases, the number of comparisons increases exponentially, making the process of comparisons long and drawn-out. Therefore, the use of AHP in this work has been confined to the derivation of weights for the sustainability aspects (techno-economic, environmental and social sustainability). The SWING method was used for weight derivation for the sustainability indicators, which is a MAVT method of weight elicitation. Stakeholders place a value of 100 on the most important indicator within the group they are assessing, and place values of less than 100 for each other indicator to reflect the relative importance. Finally, stakeholders used a rank order method in order to produce weights for the electricity options. The weighted summation method has been used for overall aggregation of stakeholder preferences (see Chapter 7 for the methodology) using Web-HIPRE tool (Mustajoki and Hamalainen, 2000).

The following sections consider different weighting placed on the sustainability indicators to gauge the influence on the overall sustainability assessment of the scenarios.

8.4.1 Equal weighting

The MCDA results for equal weighting on all the sustainability indicators and dimensions (economic, environmental and social) are displayed in Figure 8.13. The figure shows that scenario D is the preferred option, with a score of 0.7, followed by scenario C with a score of 0.61, scenario B with a score of 0.41, and finally, scenario A with a score of 0.32 (a higher score reflects a more preferable option).



Goal: 0 Sust. Energy
Segments: 2 Criteria 1
Bars: 6 Alternatives

Figure 8.13. Sustainability ranking of the four future electricity scenarios in the year 2070 with equal weights on all indicators.

The MCDA assessment shows that, for the equal weighting, scenario D performs very well for the environmental indicators (with a score of 0.31), as well as the social indicators (0.22) (although scenario C scores slightly better for the social indicators than scenario D with a score of 0.24). Scenario A has is best score for the techno-economic aspects (0.18), but scores poorly for the social and environmental categories (0.09 and 0.04, respectively). Scenario B is slightly worse than scenario A for the techno-economic aspects (displaying scores of 1.6 and 1.5, respectively), but performs much better for the social aspects (displaying scores of 0.17 and 0.09, respectively), and slightly better than scenario A for the environmental aspects (0.84 compared to 0.44), which leads to an overall better score than scenario A. Figure 8.14 shows the sensitivity analysis of the equally-weighted scenarios, for the techno-economic aspect. The figure shows that the rank order of the scenarios for the techno-economic aspect is relatively robust: the ranking of the preferred options would only change if the weighting on the techno-economic aspect changed from the current 0.33 to 0.98. In that case, scenario A would become the preferred scenario,

scenario D would be relegated to second place, B would stay in third position, and scenario C would become the least favourable option.

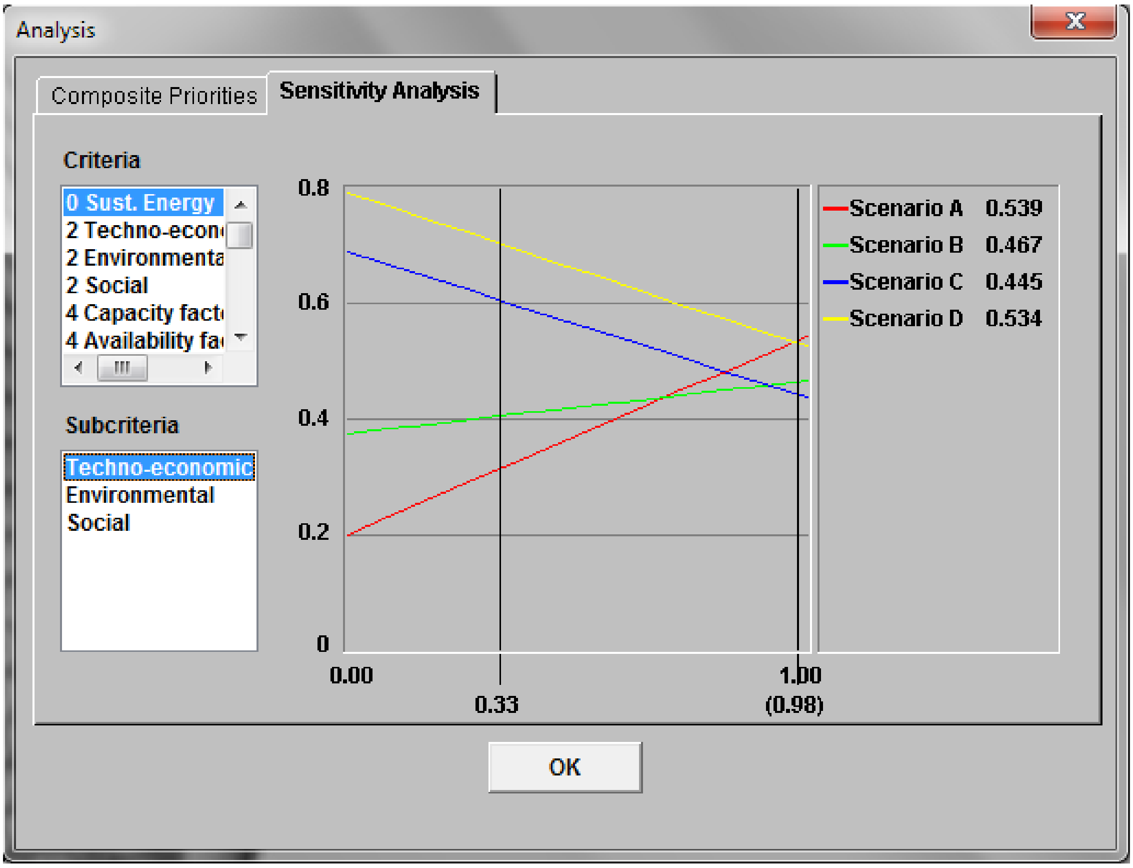
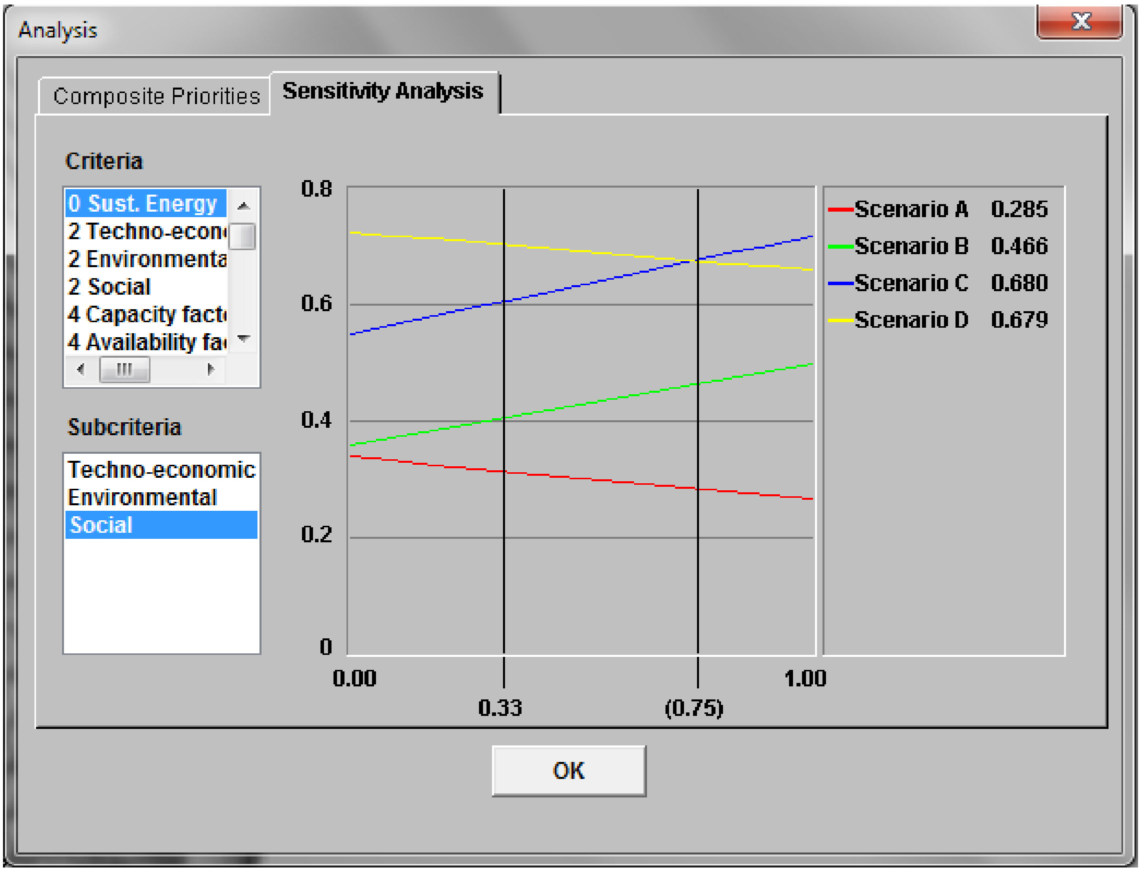


Figure 8.14. Sensitivity analysis of the four future electricity scenarios in the year 2070 with equal weights on all indicators, displayed for the techno-economic dimension. The vertical black bar labelled '0.33' represents the weight placed on the techno-economic aspect of sustainability. The vertical black bar labelled '(0.98)' represents the weight that would need to be placed on the techno-economic aspect in order to induce a rank change of the scenarios.

The sensitivity analysis of the scenario ranking for the social aspect in Figure 8.15 shows that by placing a higher weight on this aspect of sustainability (0.75 compared to 0.33), the rank of scenarios C and D would reverse so that C would become the preferred option, but the rank of scenarios A and B would remain robust. Under equal weighting, the rank order of the scenarios is robust when a change in weight of the environmental aspect is carried out.



Scenario A 0.285
Scenario B 0.466
Scenario C 0.680
Scenario D 0.679

Figure 8.15. Sensitivity analysis of the four future electricity scenarios in the year 2070 with equal weights on all indicators, displayed for the social dimension of sustainability. The vertical black bar labelled '0.33' represents the weight placed on the social aspect of sustainability. The vertical black bar labelled '(0.75)' represents the weight that would need to be placed on the social aspect in order to induce a rank change of the scenarios.

8.4.2 Expert preferences for sustainability aspects and indicators

The expert weights used in this section have been derived from Chapter 4, which details the findings of the expert MCDA questionnaire. As each expert opinion carries a large weight individually due to the knowledge and expertise that the expert possesses, the expert MCDA weights have not been averaged. Instead, using the tri-plot data on the expert weights for the sustainability aspects derived within section 4.2 of this thesis (and displayed in Figure 4.16), extremes in expert opinion on the three pillars of sustainability have been used for the weightings. Three case are considered, the first assuming an expert with techno-economic preferences, the second an expert with environmental focus, and the third an expert with strong preferences for social sustainability.

The weights used for the three case studies are displayed in Table 8.7 and reflect the extremes in opinion displayed within the tri-plot (Figure 4.16) which err most greatly towards each of the three aspects of sustainability: techno-economic, environmental and social.

Table 8.7. Case study weights of the three experts displaying extremes in opinion on the aspects (techno-economic, environmental and social) of sustainability.

Expert Stakeholder Case Study	Techno-economic Weight (%)	Environmental Weight (%)	Social Weight (%)
Techno-economic case study	74.73	19.4	5.87
Environmental case study	15.14	79.68	5.18
Social case study	5.54	20.27	74.19

8.4.2.1 Techno-economic perspective

Figure 8.16 displays the results of the sustainability assessment using weights from an expert who believes the techno-economic sustainability to be the most important aspect to consider in a sustainability assessment (these weights are displayed within Table 8.7). Scenario D is the preferred option, with an overall score of 0.71. Sceanrio C is in the second place with a score of 0.63, B is the third with 0.46, and scenario A is the worst option, with a score of 0.33. Scenario D emerges as the best option owing to the combination of high weighting on the techno-economic aspect (0.75) and high weights and scores for the indicators for which it performs well: fuel costs, total levelised costs and lifetime of fuel reserves place this scenario as first in rank of preferred options.

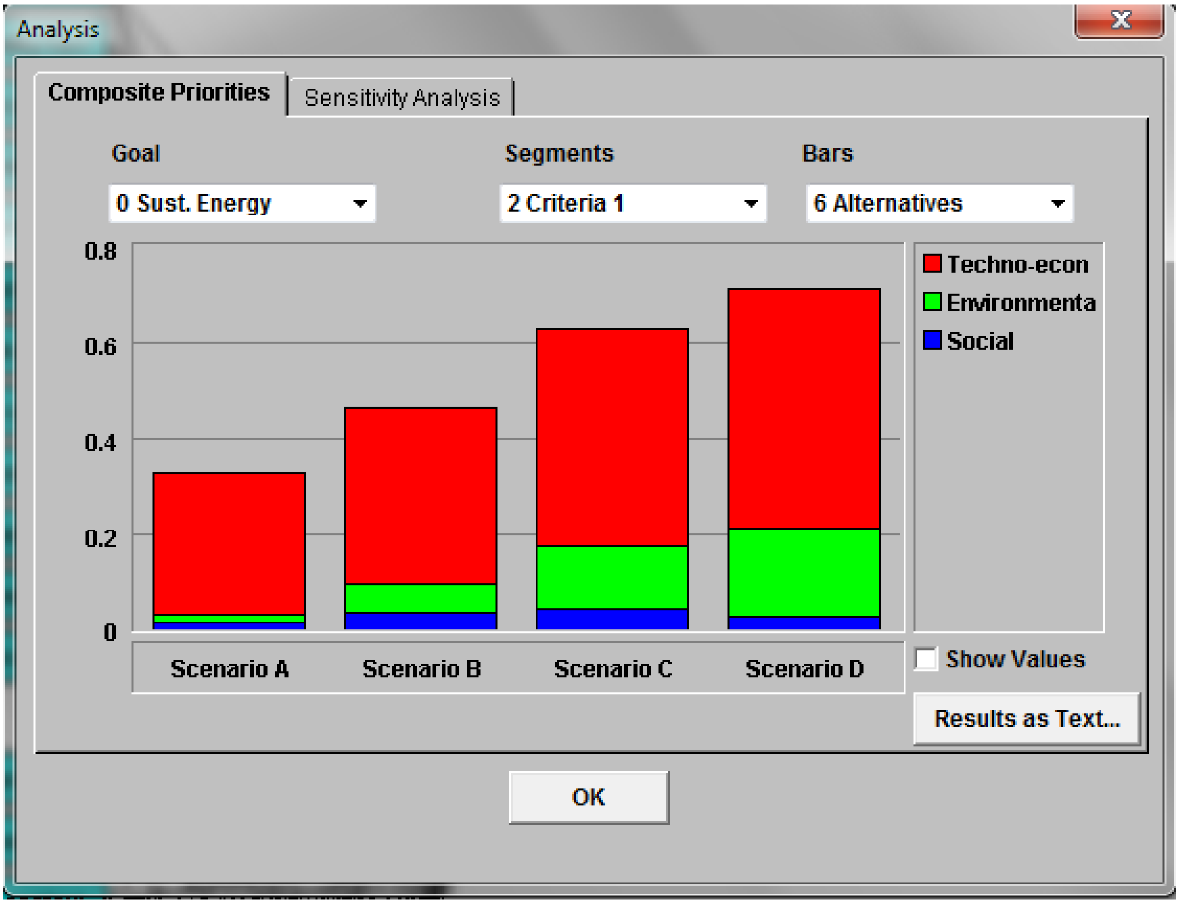


Figure 8.16. Sustainability ranking of the four future electricity scenarios in the year 2070 with expert preferences (with a techno-economic bias) applied to all indicators and dimensions of sustainability.

A sensitivity analysis of this assessment for the weighting for the social aspects of sustainability can be seen in Figure 8.17. The assessment shows that an increase in weight on the social aspect of sustainability from 0.06 (current weight), to 0.29 would induce a change in ranking – scenario C would then become the preferred option. If an even higher weight was placed on social sustainability (0.64), scenario D would be placed in the third place. Sensitivity analyses carried out on the techno-economic and environmental aspects of sustainability show that the preference order is not at all sensitive to a change in weight on either of these aspects.

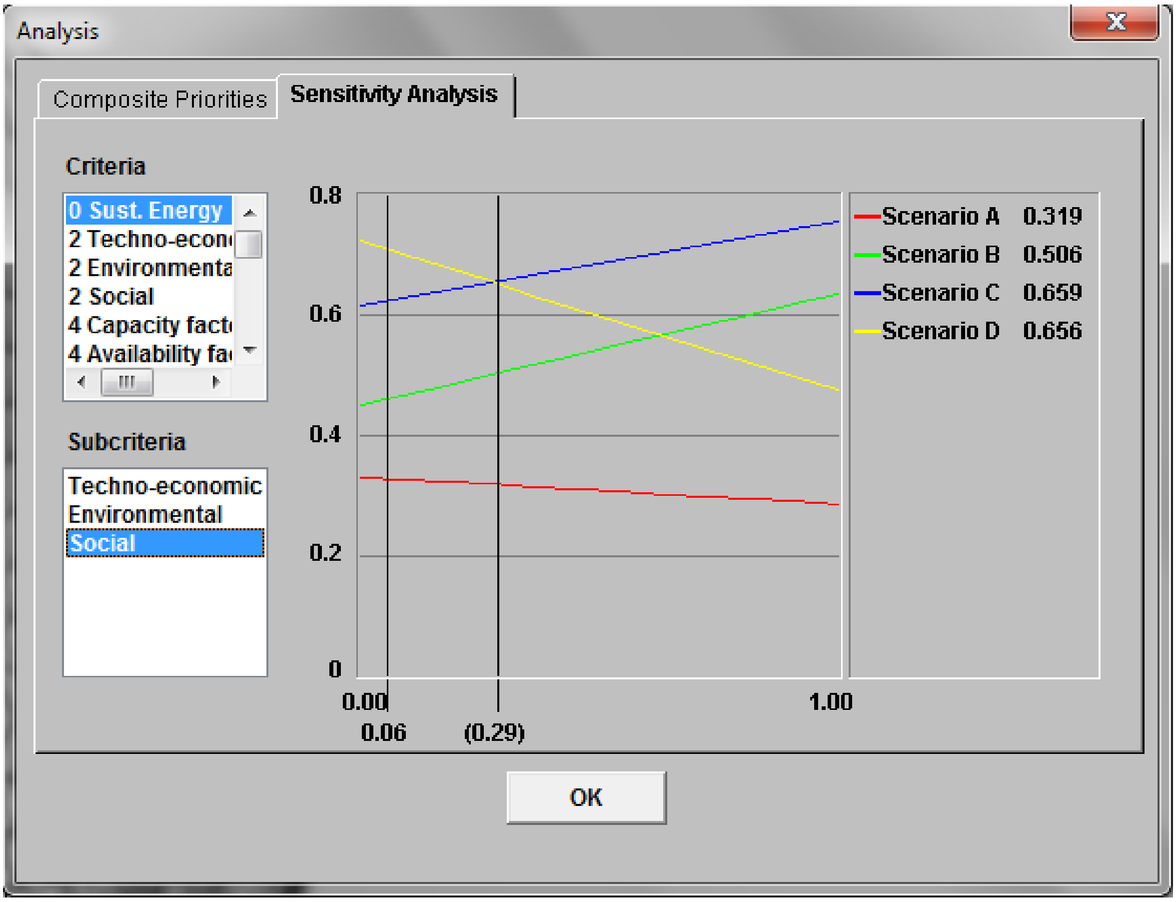
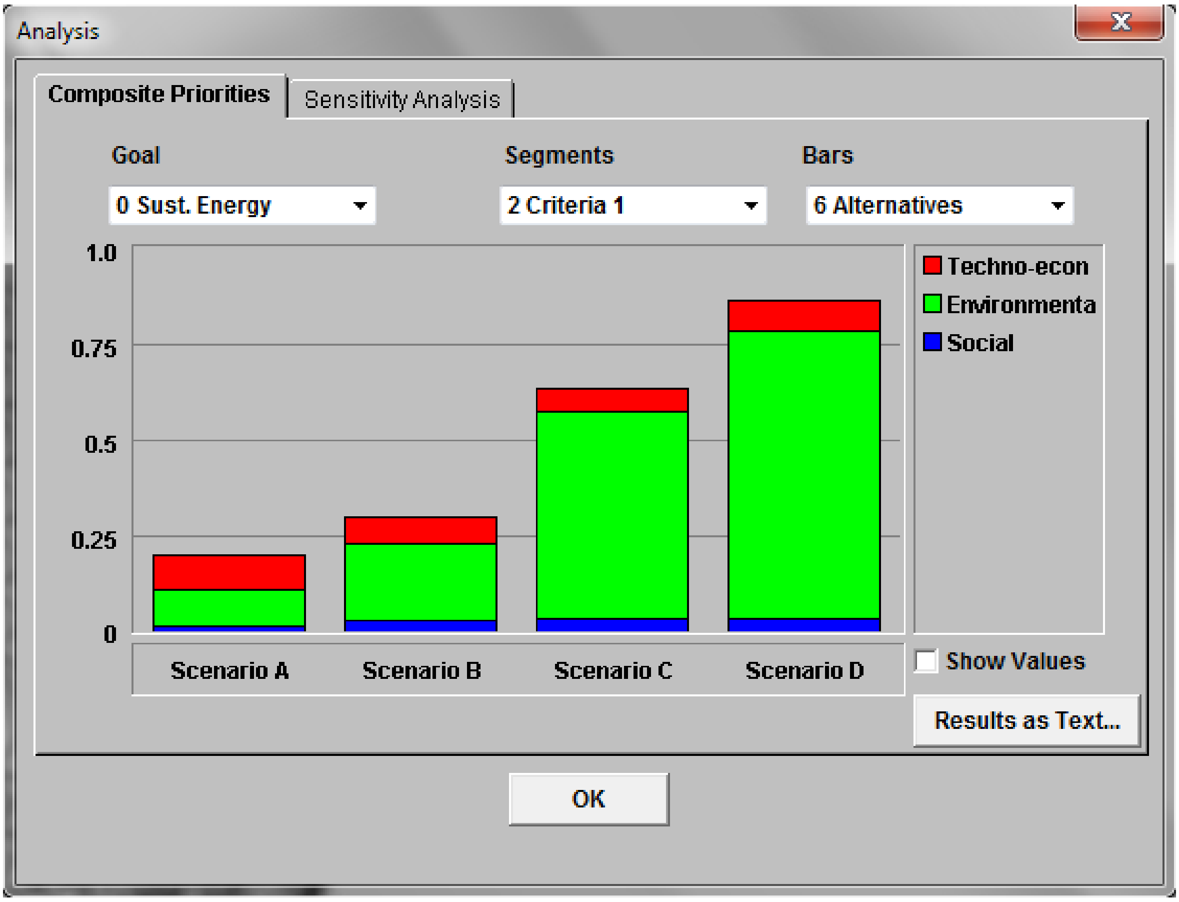


Figure 8.17. Sensitivity analysis of the four future electricity scenarios in the year 2070 with expert weights on the indicators and sustainability pillars (with a techno-economic bias), displayed for the social dimension of sustainability. The vertical black bar labelled '0.06' represents the weight placed on the social aspect of sustainability. The vertical black bar labelled '(0.29)' represents the weight that would need to be placed on the social aspect in order to induce a rank change of the scenarios.

8.4.2.2 Environmental perspective

The results of the environmental focus case study of one expert show that the same rank order is obtained for the scenarios as for the techno-economic focus (see Figure 8.18). Scenario D scores best overall with 0.87, scenario C 0.64, scenario B 0.30, and scenario A scores 0.20. The performance of this scenario for indicators such as GWP and many other environmental indicators, combined with a high weight placed on these indicators and the environmental sustainability makes this scenario the preferred option overall.



Goal: 0 Sust. Energy

Segments: 2 Criteria 1

Bars: 6 Alternatives

Figure 8.18. Sustainability ranking of the four future electricity scenarios in the year 2070 with expert preferences (with an environmental bias) applied to all indicators and dimensions of sustainability.

A sensitivity analysis (Figure 8.19) on the rank of the scenarios with weight on the techno-economic aspect of sustainability shows that the dominance of scenario D is relatively robust – a large weight (0.96) would have to be placed on techno-economic sustainability to induce a rank change in most preferable scenario from D to scenario A.

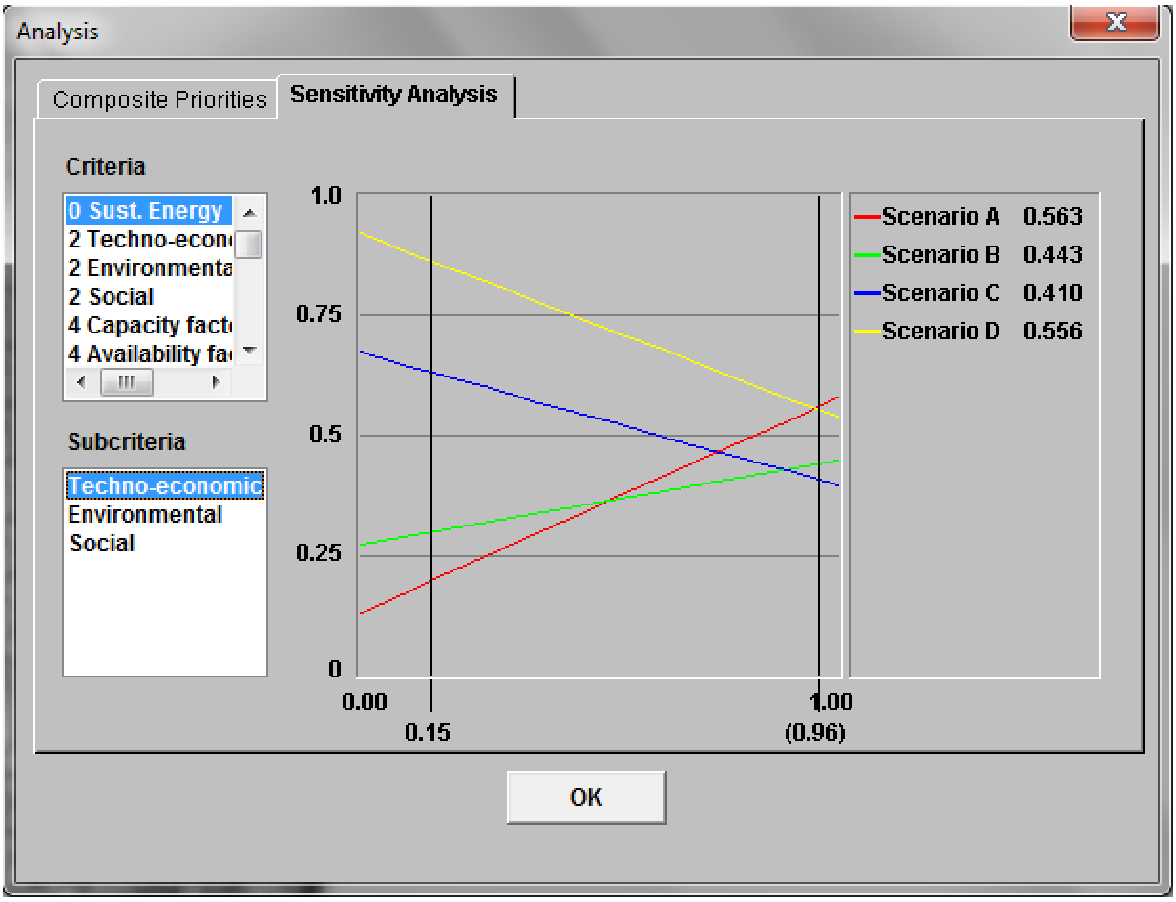


Figure 8.19. Sensitivity analysis of the four future electricity scenarios in the year 2070 with expert weights on the indicators and sustainability pillars (with an environmental bias), displayed for the techno-economic aspect of sustainability. The vertical black bar labelled '0.15' represents the weight placed on the techno-economic aspect of sustainability. The vertical black bar labelled '(0.96)' represents the weight that would need to be placed on the techno-economic aspect in order to induce a rank change of the scenarios.

A change in weighting on the environmental aspect within this case study would also induce a change in rank of scenarios A and B, and with an extreme change in weight, scenario C would also be affected. This can be seen in Figure 8.20. If the weight on the environmental aspect is decreased from 0.8 down to 0.16, scenarios A and B switch rank, with scenario A becoming preferable to scenario B. If this weight decreases to 0.03, scenario A then becomes the second in rank after scenario D.

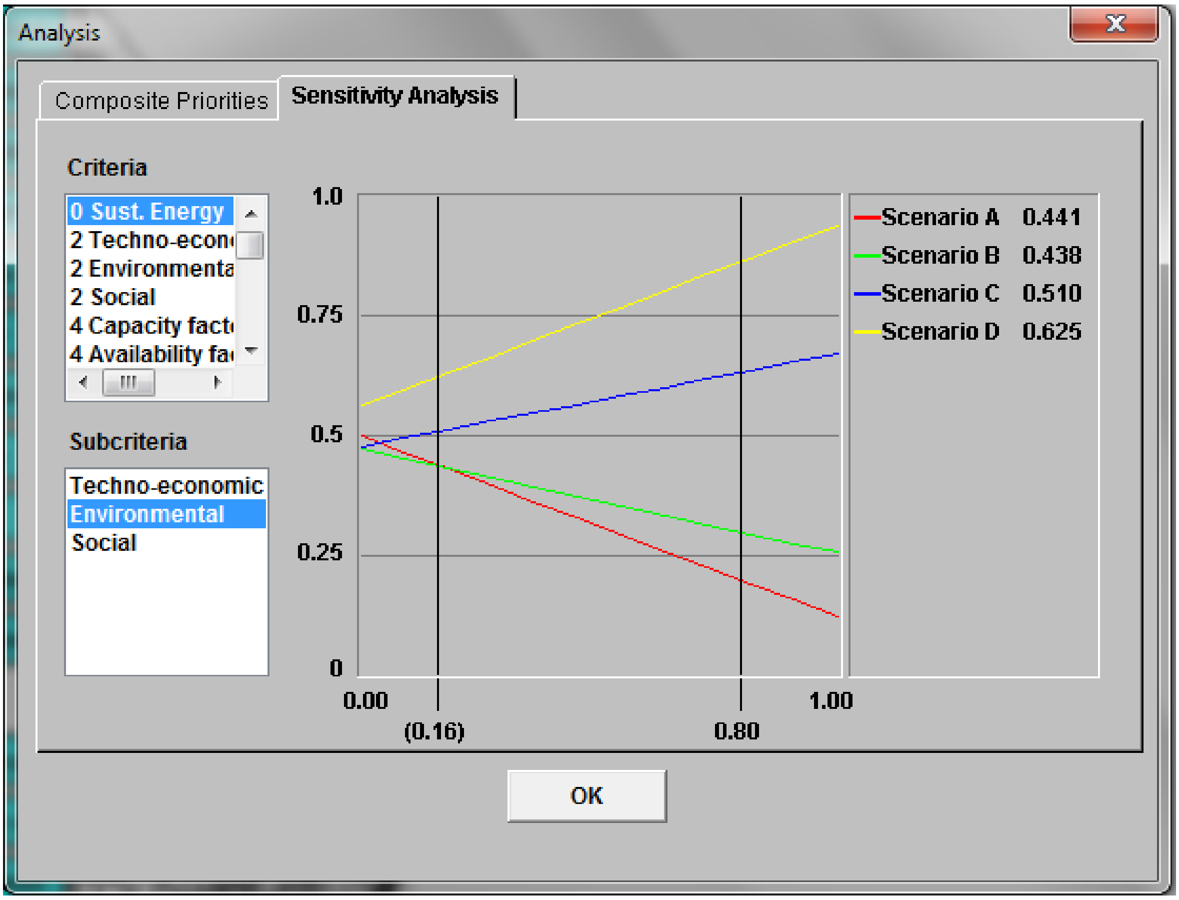
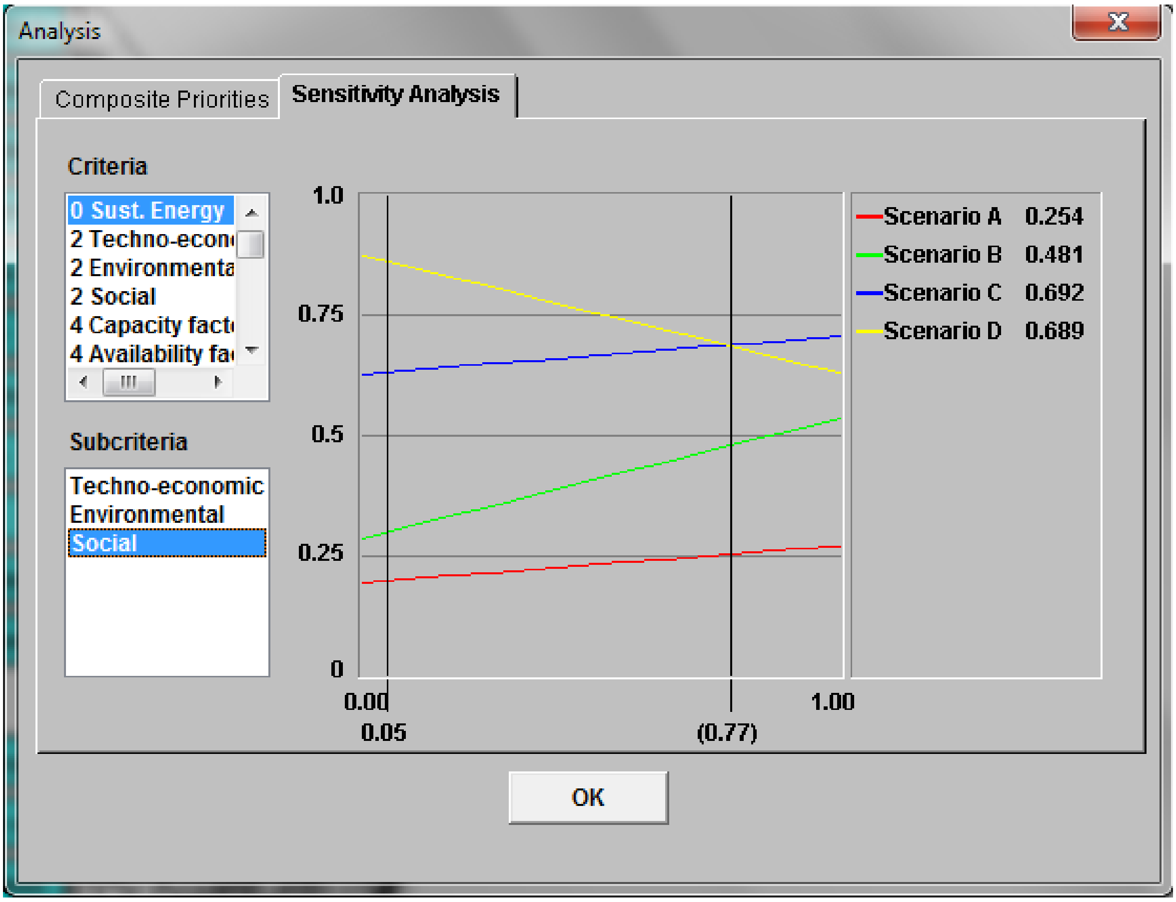


Figure 8.20. Sensitivity analysis of the four future electricity scenarios in the year 2070 with expert weights on the indicators and sustainability pillars (with an environmental bias), displayed for the environmental aspect of sustainability. The vertical black bar labelled '0.80' represents the weight placed on the environmental aspect of sustainability. The vertical black bar labelled '(0.16)' represents the weight that would need to be placed on the environmental aspect in order to induce a rank change of the scenarios.

Results of the sensitivity analysis for this case study also showed that the rank of the scenarios would change if the weight on the social aspect of sustainability increased significantly (this is displayed in Figure 8.21). An increase in weight on social sustainability from 0.05 to 0.77 would mean that scenario C would become the preferred option over scenario A.

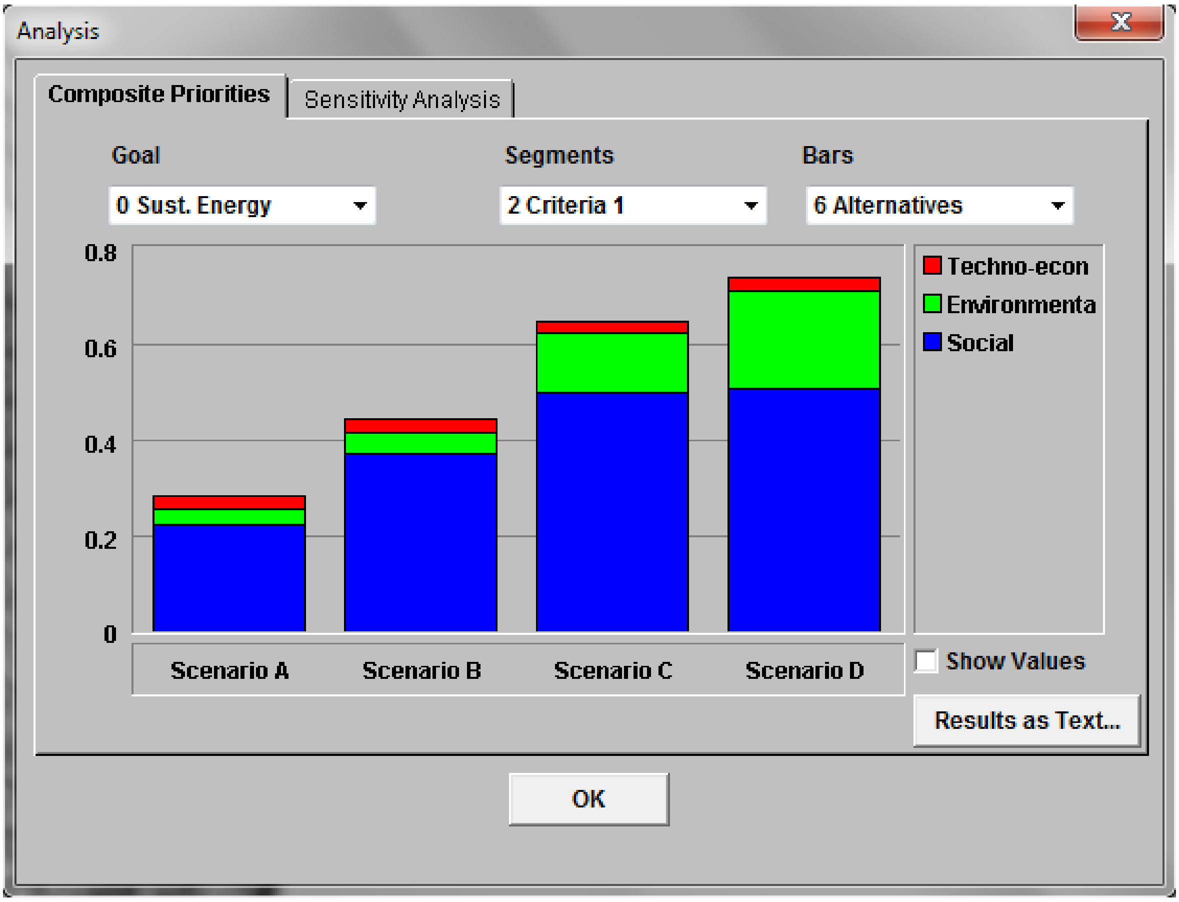


Scenario A 0.254
Scenario B 0.481
Scenario C 0.692
Scenario D 0.689

Figure 8.21. Sensitivity analysis of the four future electricity scenarios in the year 2070 with expert weights on the indicators and sustainability pillars (with an environmental bias), displayed for the social dimension of sustainability. The vertical black bar labelled '0.05' represents the weight placed on the social aspect of sustainability. The vertical black bar labelled '(0.77)' represents the weight that would need to be placed on the social aspect in order to induce a rank change of the scenarios.

8.4.2.3 Social perspective

The results of the MCDA carried out with a high social weighting from an experts' perspective are displayed in Figure 8.22. Again, scenario D dominates the other scenarios as the preferred option with a score of 0.74. Scenario C is the next preferred option, with a score of 0.65, followed by scenario B (0.44) and finally, scenario A (0.28). High weightings combined with good scores on the social indicators (volume of CO_2 to be stored; abiotic fossil fuel depletion; fuel storage capability; fossil fuels avoided; large accident fatalities; human toxicity potential; and worker injuries) place this scenario above all others in this analysis.



Goal: 0 Sust. Energy

Segments: 2 Criteria 1

Bars: 6 Alternatives

Figure 8.22. Sustainability ranking of the four future electricity scenarios in the year 2070 with expert preferencess (with a social bias) applied to all indicators and dimensions of sustainability.

A sensitivity analysis carried out on the ranking of the scenarios using the socially-biased weights for the techno-economic aspect can be seen in Figure 8.23. This analysis shows that the results are relatively robust – the weight on the techno-economic indicators would have to change significantly (to 0.97) to produce a change in rank of the scenarios, promoting scenario A from the worst to the best option. Sensitivity analyses carried out on the environmental and social aspects of sustainability show that the preference order is not at all sensitive to a change in weight on either of these aspects.

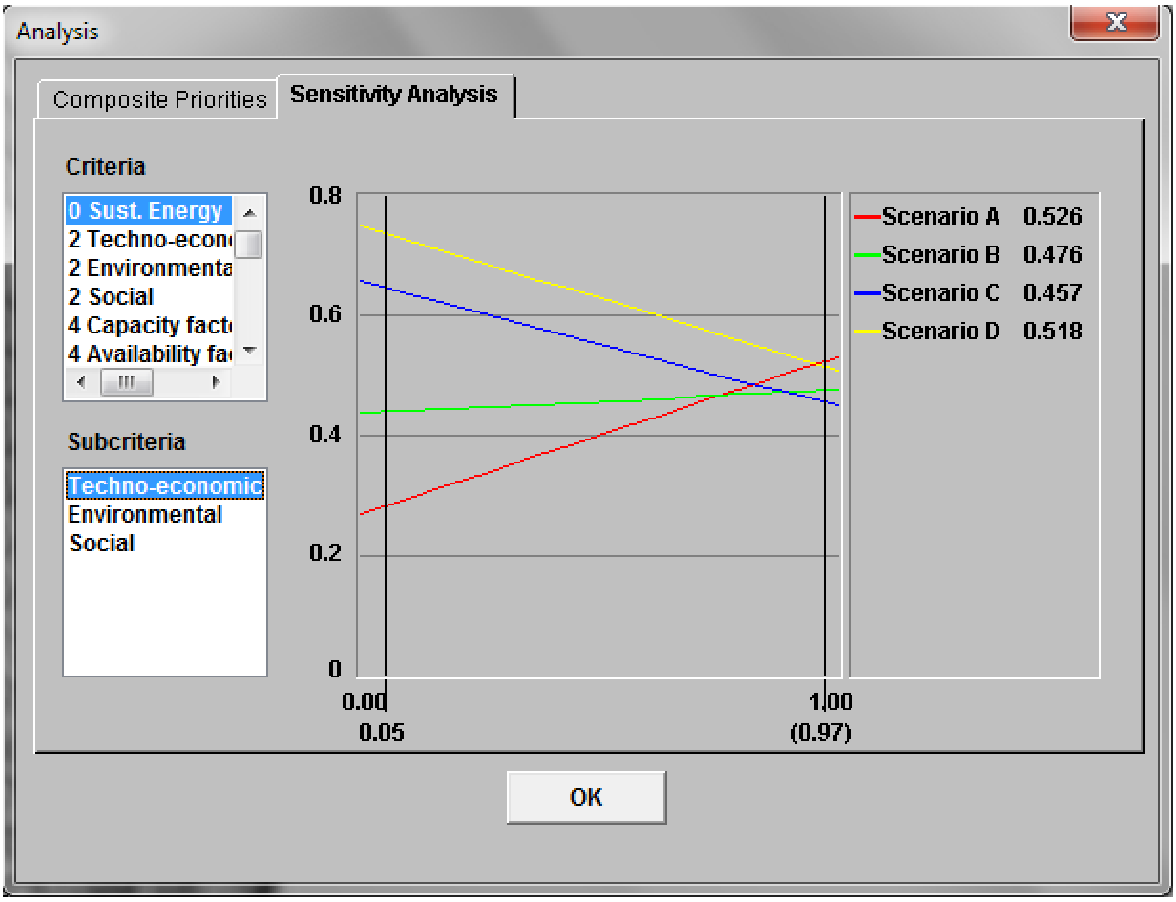


Figure 8.23. Sensitivity analysis of the four future electricity scenarios in the year 2070 with expert weights on the indicators and sustainability pillars (with a social bias), displayed for the techno-economic aspect of sustainability. The vertical black bar labelled '0.05' represents the weight placed on the techno-economic aspect of sustainability. The vertical black bar labelled '(0.97)' represents the weight that would need to be placed on the techno-economic aspect in order to induce a rank change of the scenarios.

8.4.3 <u>Expert preferences for electricity-generating technologies</u>

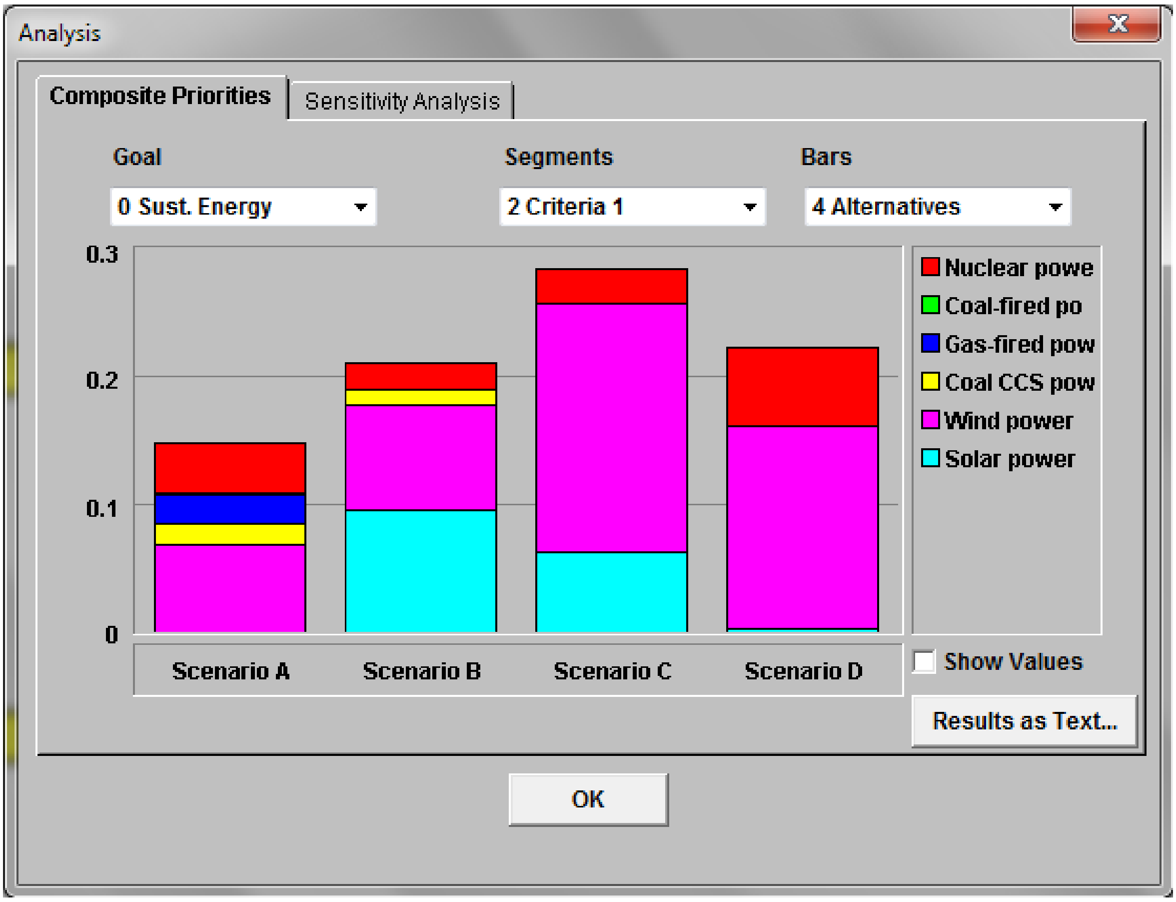
The weights used for the three case studies are displayed in Table 8.8 and reflect each individual's opinion towards each of the technology options used within all four scenarios.

Table 8.8. Expert weights for the electricity technology options displayed under the three experts MCDA case studies: techno-economic; environmental; and social perspectives.

Technology Type	Techno-economic Case Study	Environmental Case Study	Social Case Study
Nuclear power weight (%)	10.3	2.8	15.8
Coal-fired power weight (%)	2.8	10.3	2.8
Gas-fired power weight (%)	15.8	24.2	6.1
Coal CCS power weight (%)	6.1	15.8	10.3
Wind power weight (%)	40.8	40.8	24.2
Solar power weight (%)	24.2	6.1	40.8

8.4.3.1 Techno-economic perspective

The views of the expert with an extreme techno-economic bias are modelled on the electricity-generating options under each of the developed scenarios and are displayed in Figure 8.24. The figure shows that under this expert's opinion on the favourability of each electricity option within the scenarios, scenario C is the most preferred alternative, with a score of 0.29, followed by scenario D (0.22), scenario B (0.21) and scenario (0.15). This result contrasts somewhat with the sustainability ranking of the scenarios based on this individual's weighting modelled on the sustainability indicators and aspects, where scenario D was the most preferred option, followed by C, then B, and finally, A.



Goal: 0 Sust. Energy

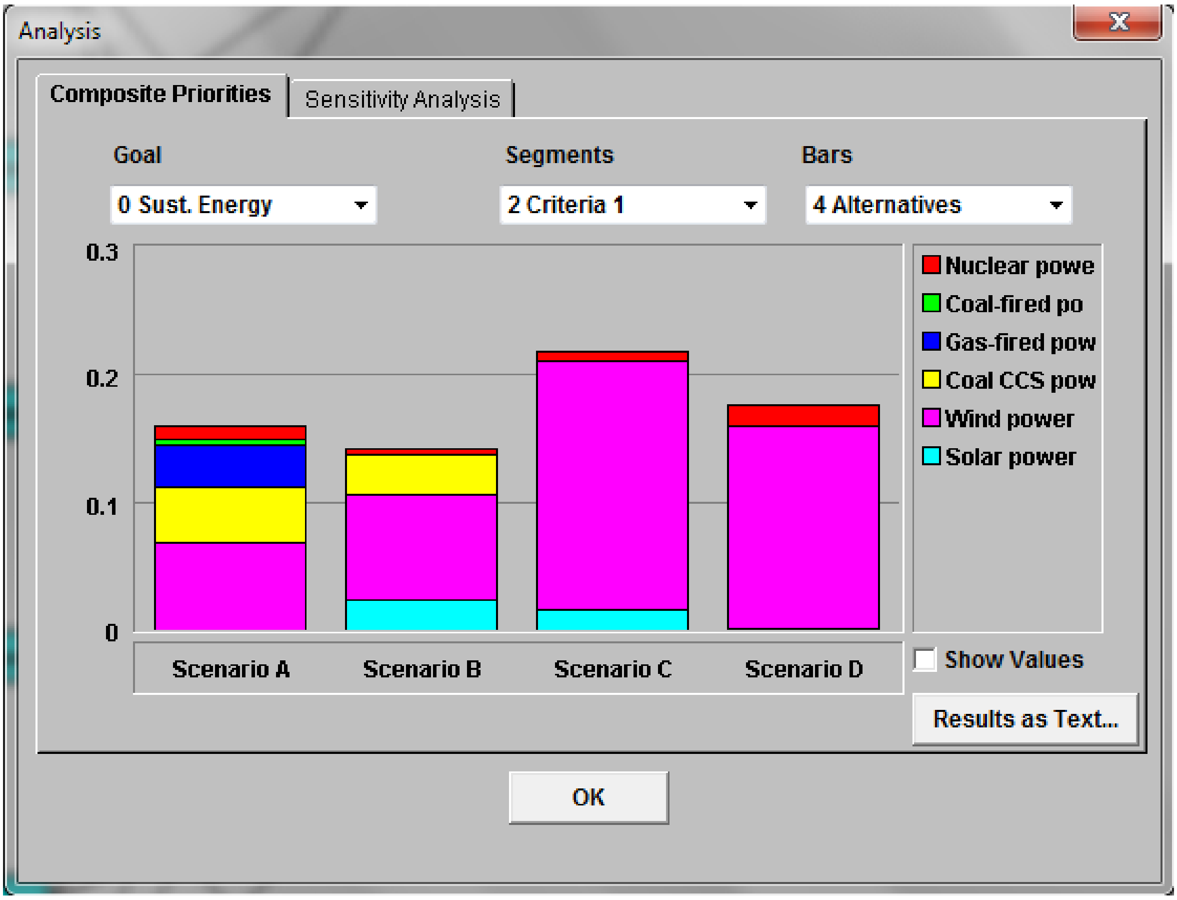
Segments: 2 Criteria 1

Bars: 4 Alternatives

Figure 8.24. Sustainability ranking of the four future electricity scenarios in the year 2070 based on expert ranking of the electricity options, from a techno-economic perspective.

8.4.3.2 Environmental perspective

The results of the sustainability ranking based on the expert's opinion with environmental leanings using the ranking derived for the electricity options are displayed in Figure 8.25. Scenario C is the most preferred option, with a score of 0.22, followed by scenario D (1.8), then scenario A (0.16, and finally, scenario B (0.14). This individual has a high favourability of wind power, which has highest penetration in scenario C.



Goal: 0 Sust. Energy

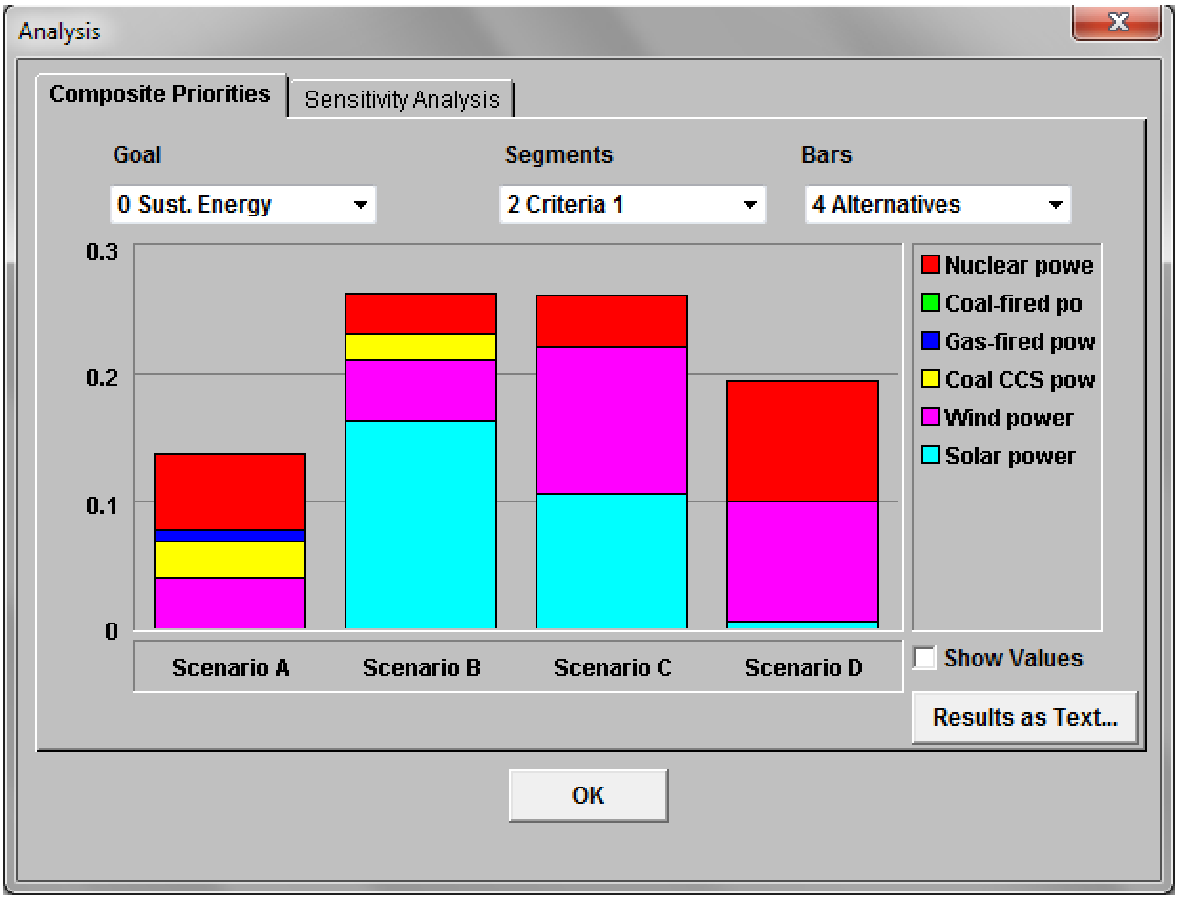
Segments: 2 Criteria 1

Bars: 4 Alternatives

Figure 8.25. Sustainability ranking of the four future electricity scenarios in the year 2070 based on expert ranking of the electricity options, from an environmental perspective.

8.4.3.3 Social perspective

The results of the sustainability ranking of the future electricity scenarios, modelled using weights placed on the electricity options from the perspective of an expert with social sustainability leanings are displayed in Figure 8.26. The results show scenario B as the most preferred option (0.264), followed closely by scenario C (0.263), scenario D (0.2) and scenario A (0.14). scenario B becomes the most preferred option under this individual’s weighting on the electricity options due to their favourable opinion of solar power, which has its highest penetration in scenario B. This expert also has a relatively high opinion of wind power, making scenario C the next preferred option.



Goal: 0 Sust. Energy

Segments: 2 Criteria 1

Bars: 4 Alternatives

Figure 8.26. Sustainability ranking of the four future electricity scenarios in the year 2070 based on expert ranking of the electricity options, from a social perspective.

8.4.4 Public preferences for sustainability aspects and indicators

The weights for this analysis have been taken from the work carried out on the public perspectives of electricity-generating technologies and their sustainability impacts, detailed in Chapter 5. In order to reflect a democratic vote on the variety of sustainability impacts, sustainability aspects and electricity-generating technologies, the public preferences have been averaged across the total sample in order to derive an average weight. The average weights for each aspect of sustainability are displayed in Table 8.9. The results of the MCDA using average public opinion are shown in Figure 8.27.

Table 8.9. Public case study weights on the aspects (techno-economic, environmental and social) of sustainability.

Expert Stakeholder Case Study	Techno-economic Weight (%)	Environmental Weight (%)	Social Weight (%)
Public average weight	20.92	55.26	23.83

As can be seen from Figure 8.27, with a score of 0.77, scenario D is most sustainable option. Scenario C is second best, with 0.62. This is followed by scenario B with 0.37 and finally, scenario A, which has a score of 0.25.

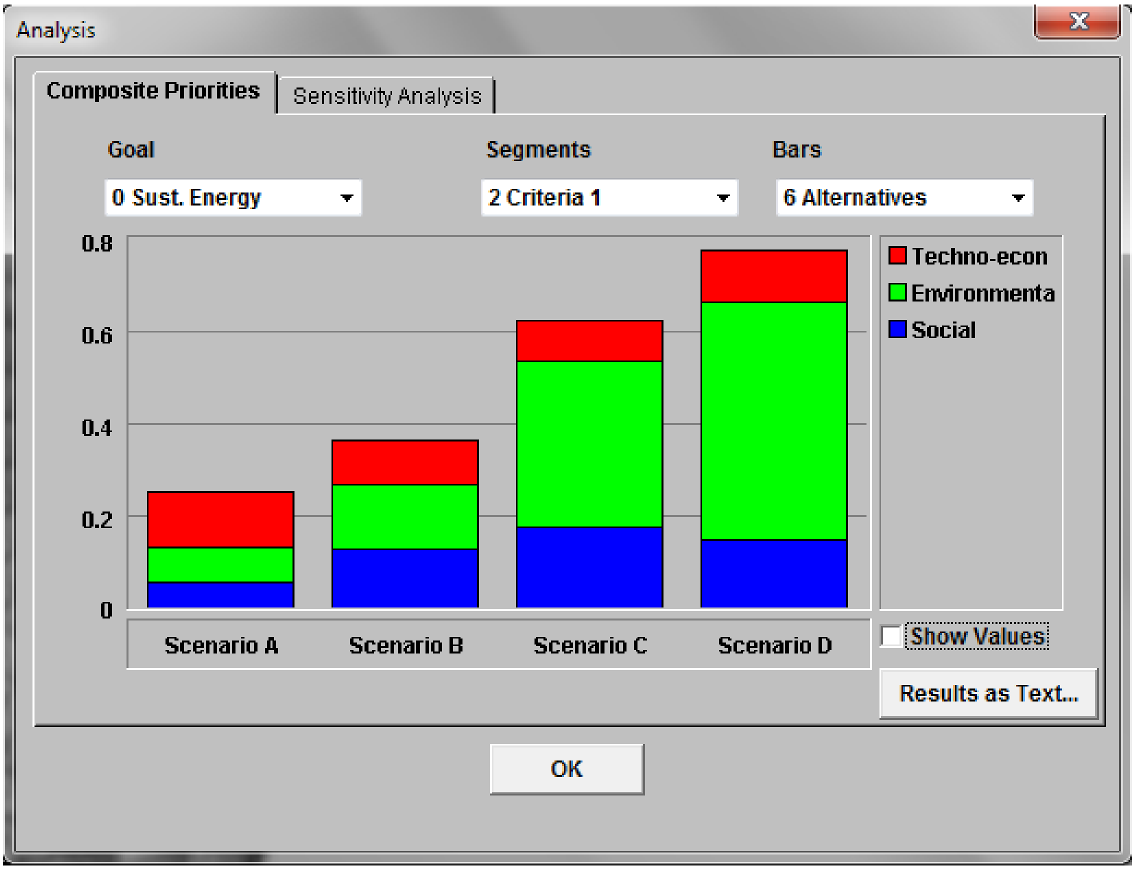

Goal: 0 Sust. Energy
Segments: 2 Criteria 1
Bars: 6 Alternatives

Figure 8.27. Sustainability ranking of the four future electricity scenarios in the year 2070 based on the public preferences applied to all indicators and dimensions of sustainability.

The public preferences indicate a large focus on the environmental indicators, for which scenario D performs well (as evident from the equal weighting); therefore, the performance of this scenario is maximised when public opinion is taken into account. Scenario C also scores well due to its environmental performance, compared to scenarios A and B.

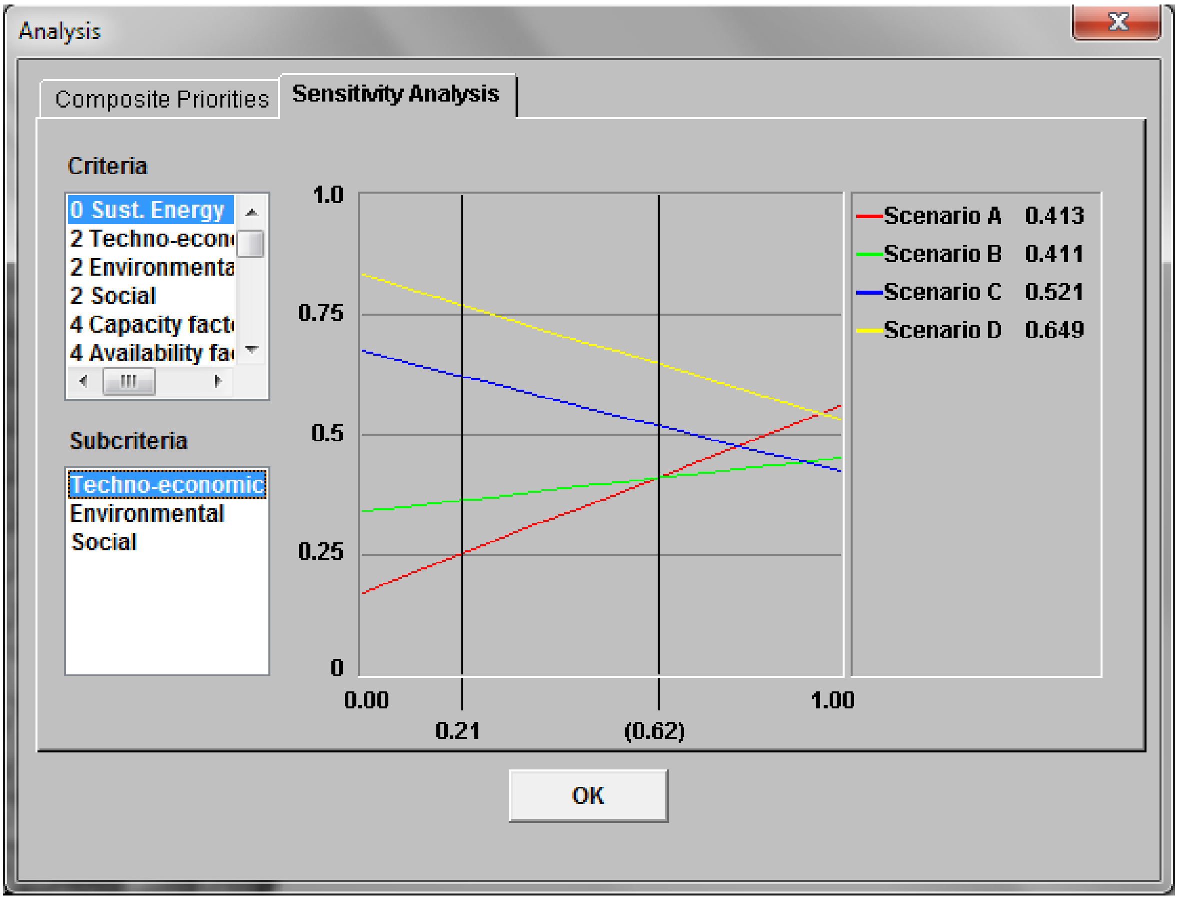


Figure 8.28. Sensitivity analysis of the four future electricity scenarios in the year 2070 with public preferences for the indicators and sustainability dimensions, displayed for the techno-economic dimension. The vertical black bar labelled ‘0.21’ represents the weight placed on the techno-economic aspect of sustainability. The vertical black bar labelled ‘(0.62)’ represents the weight that would need to be placed on the techno-economic aspect in order to induce a rank change of the scenarios.

A sensitivity analysis of the public weighting under the techno-economic weight is displayed in Figure 8.28. This sensitivity analysis shows that is focus was almost solely placed on the techno-economic aspect of sustainability (a weight of 0.97), then scenario A would become the most preferred option out of all scenarios. A weight of 0.62 on the techno-economic aspect would initiate a rank reversal for scenarios A and B.

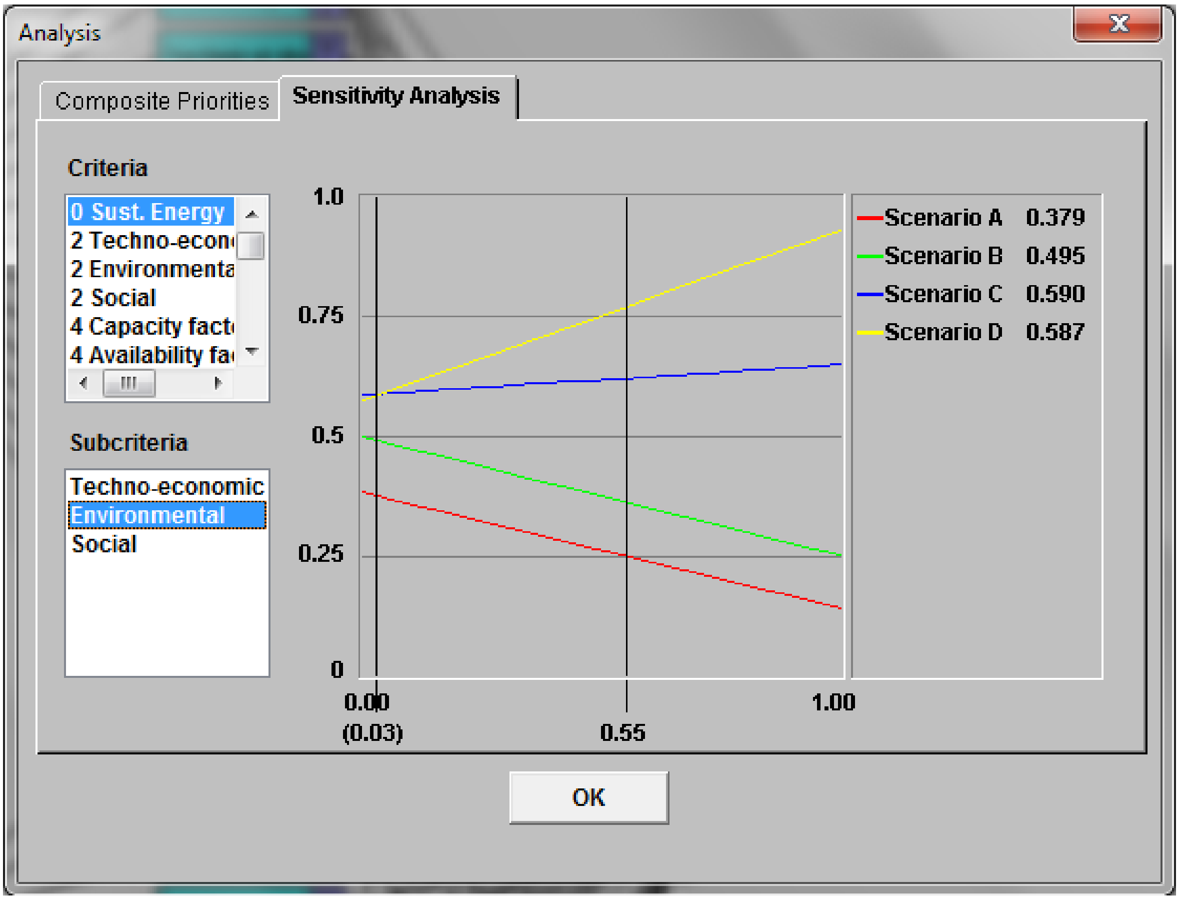


Figure 8.29. Sensitivity analysis of the four future electricity scenarios in the year 2070 with public preferences for the indicators and sustainability dimensions, displayed for the environmental dimension. The vertical black bar labelled '0.55' represents the weight placed on the environmental aspect of sustainability. The vertical black bar labelled '(0.03)' represents the weight that would need to be placed on the environmental aspect in order to induce a rank change of the scenarios.

Sensitivity analysis on the environmental aspect of sustainability under the average public weighting is displayed in Figure 8.29. This analysis shows that the results of the MCDA under the environmental dimension are relatively robust – the weight on environmental aspects would need to be reduced to 0.03 in order for scenario C to become the preferred option, over scenario D.

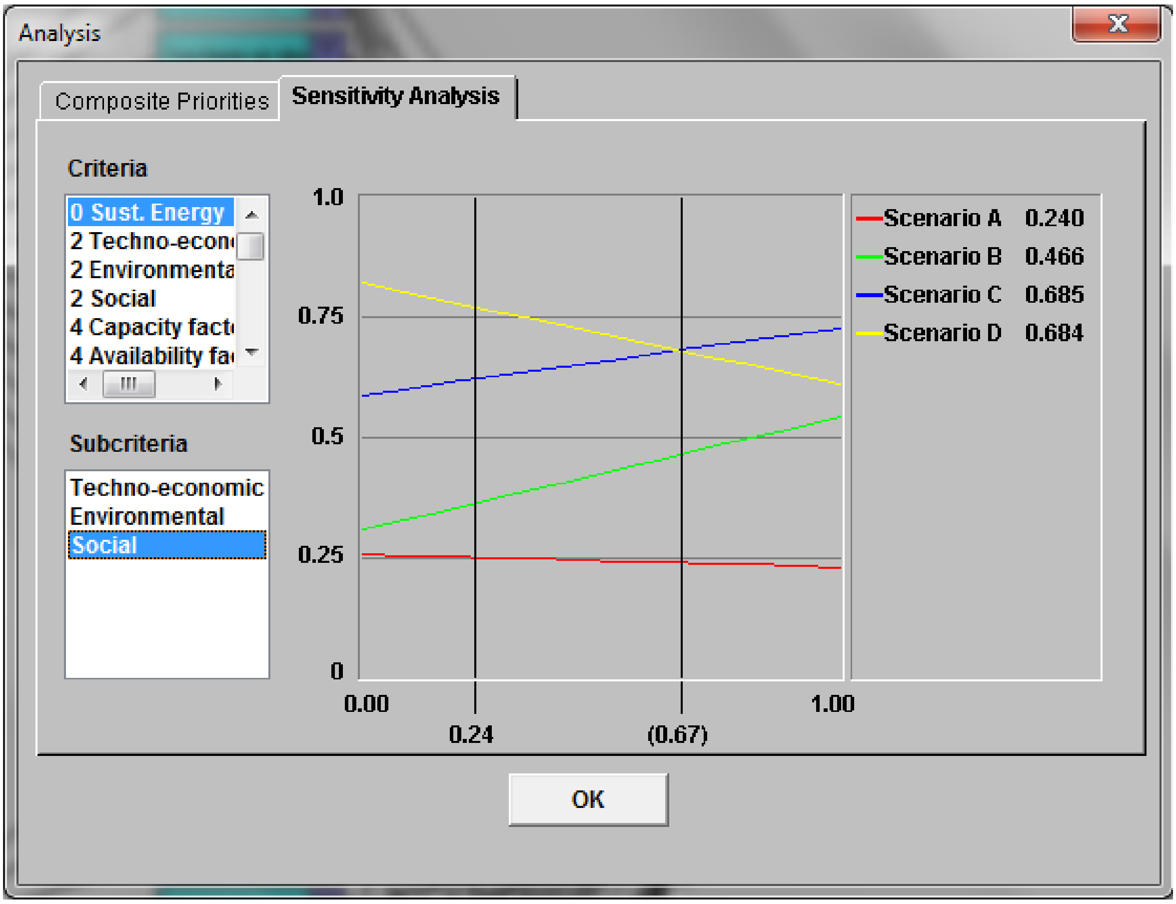


Figure 8.30. Sensitivity analysis of the four future electricity scenarios in the year 2070 with public preferences for the indicators and sustainability dimensions, displayed for the social dimension. The vertical black bar labelled '0.24' represents the weight placed on the social aspect of sustainability. The vertical black bar labelled '(0.67)' represents the weight that would need to be placed on the social aspect in order to induce a rank change of the scenarios.

The sensitivity analysis for the social aspect of sustainability for the average public weight displays sensitivity of scenarios C and D. Under the average weight, scenario D is the preferred option, but if this weight was increased to 0.67 or higher, scenario C would become the preferred option.

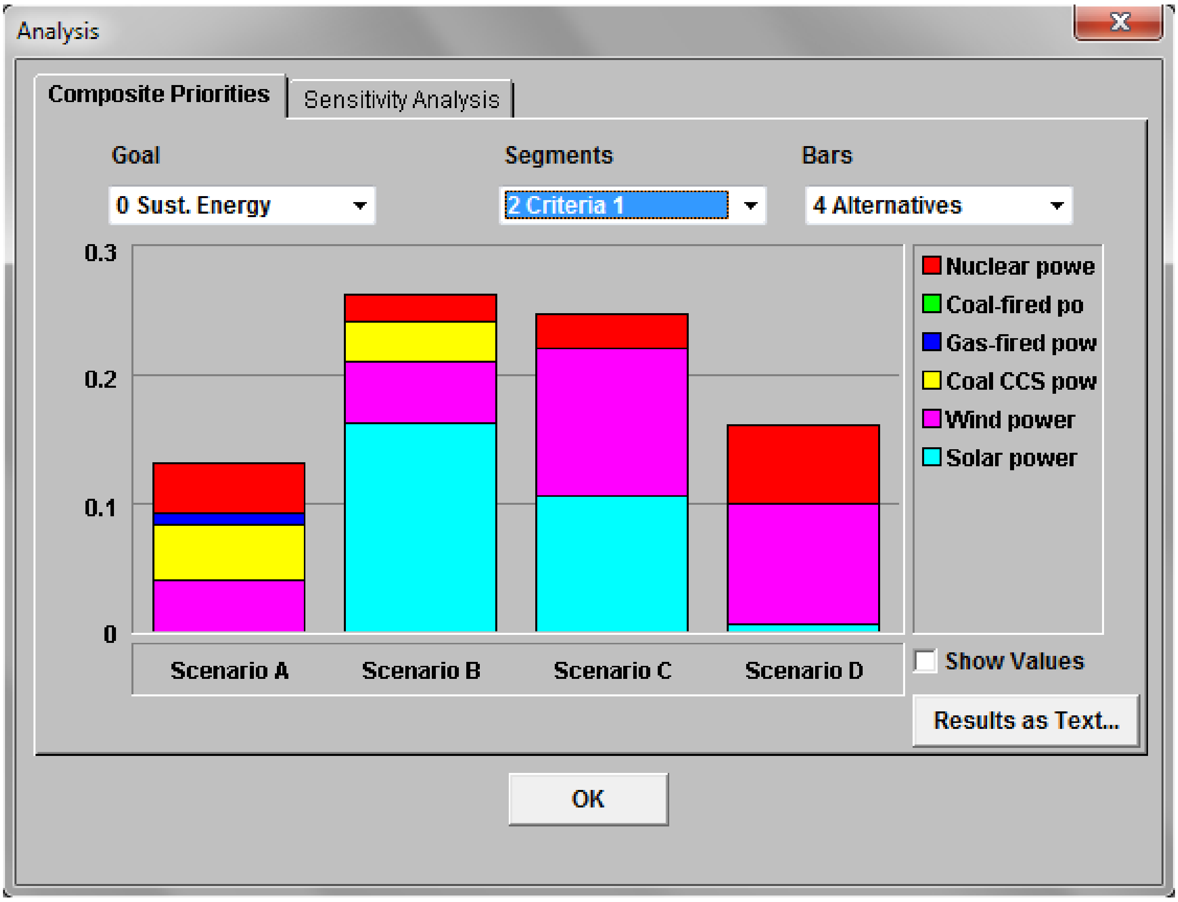
8.4.5 Public preferences for electricity-generating technologies

In addition to the MCDA analyses carried out on the future electricity options using weights on the sustainability indicators and aspects in the previous section, an MCDA is also carried out here using the public ranking of the electricity-generating technologies (discussed in Chapter 5) and their contributions to each scenario, to indicate which would be the preferred scenario based solely on opinion of electricity options. The average weights are displayed in Table 8.10.

Table 8.10. Public average weights for the electricity technology options.

Technology Type	Average Public Weight (%)
Nuclear power weight (%)	10.3
Coal-fired power weight (%)	2.8
Gas-fired power weight (%)	6.1
Coal CCS power weight (%)	15.8
Wind power weight (%)	24.2
Solar power weight (%)	40.8

Figure 8.31 shows that, based on the public opinion of the electricity technologies, scenario B becomes the preferred scenario with a score of 0.26, closely followed by scenario C (0.25); scenario D scores 0.16 and scenario A 0.13. Scenario B has the highest score due to the high penetration of solar power within this scenario (40%) and the favourable public opinion on solar power (see Table 8.10). Scenario C also performs well due to the high penetration of solar and wind, the latter of which is also favoured by the public. Scenario A performs the worst due to the most carbon-intensive electricity mix and the related technologies which are unfavourable to the public. Compared to its position as the preferred option based on the sustainability assessment using the sustainability indicators (previous section), scenario D comes in third place when basing the assessment on preference of technologies. This is due to the lower penetration of renewable technologies within this scenario, which are replaced to a large extent by nuclear power (59.5% penetration within this scenario) for which the public opinion is only moderately favourable (see Table 8.10).



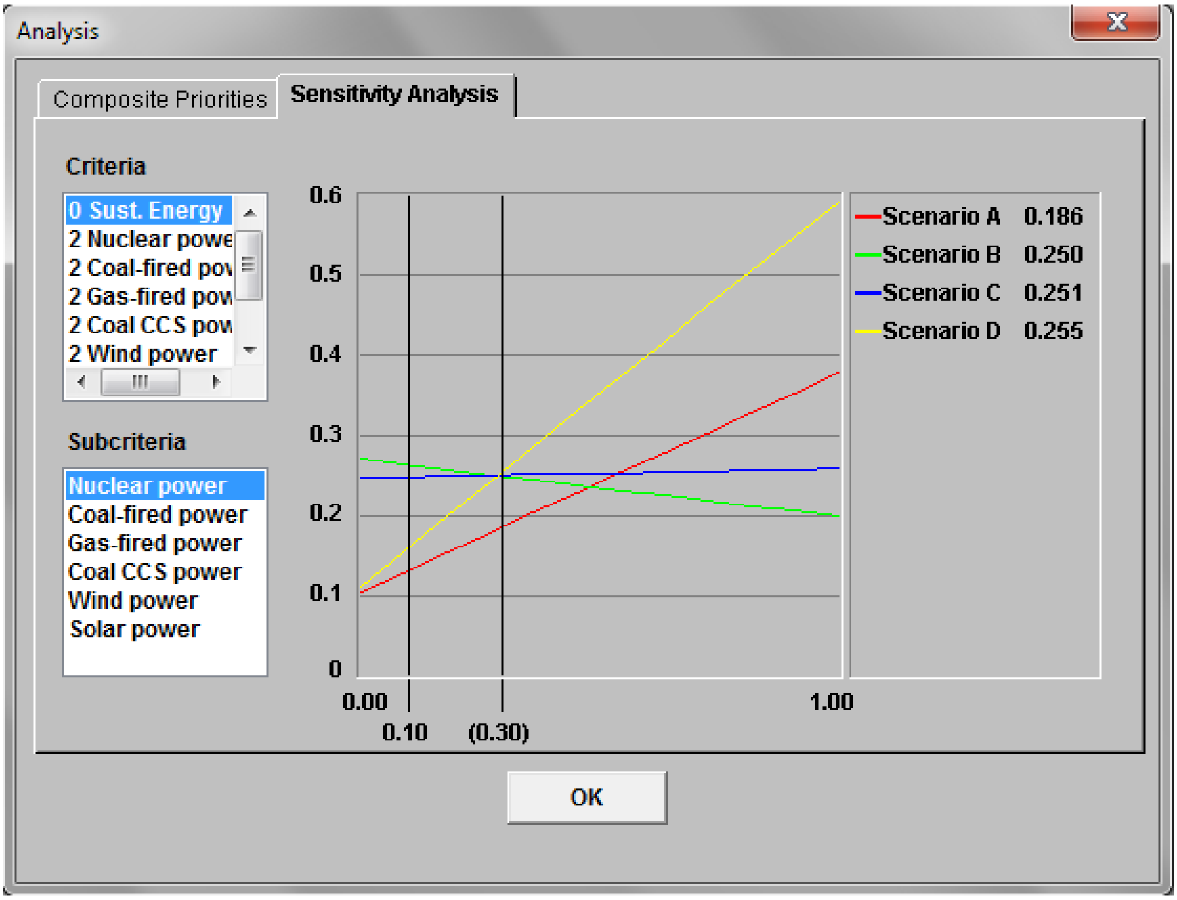
Goal: 0 Sust. Energy

Segments: 2 Criteria 1

Bars: 4 Alternatives

Figure 8.31. Sustainability ranking of the four future electricity scenarios in the year 2070 based on public ranking of the electricity options.

A sensitivity analysis of the sustainability ranking using weights placed on the electricity technologies is displayed in Figure 8.32. This shows that varying the weight placed on nuclear power can induce a rank change of the scenarios. Scenario D would dominate with a preference weighting on this technology of more than 0.30 (i.e. more favourable public opinion on nuclear power), compared to its current weight of 0.10. Reducing the weighting on nuclear power (i.e. less favourable public opinion than currently) would make no change to the ranking of scenario D. Therefore, these findings suggest that more favourable public opinion of nuclear power could help towards Government support for this electricity option; the reverse would have no effect.



Scenario A 0.186
Scenario B 0.250
Scenario C 0.251
Scenario D 0.255

Figure 8.32. Sensitivity analysis of the four future electricity scenarios in the year 2070 with public weights on the electricity-generating options, displayed for the nuclear power aspect of sustainability. The vertical black bar labelled '0.10' represents the weight placed on nuclear power. The vertical black bar labelled '(0.30)' represents the weight that would need to be placed on nuclear power in order to induce a rank change of the scenarios.

8.5 Summary

The multi-criteria decision analysis of future electricity options carried out in this chapter, based on: equal weighting of the sustainability indicators and aspects; several expert case studies; and average public preferences have displayed how electricity decisions for the future may be affected by input from these groups of stakeholders.

Equal weighting of the sustainability indicators and aspects showed that scenario D was the preferred scenario, followed by scenario C, then B and finally, A. This is due to the environmental performance of the scenarios which contain the highest penetrations of 'greener' technologies (nuclear, offshore wind and solar power). These results are relatively robust, the rank only changes with a very high techno-economic weight, where scenario A becomes the preferred option and with a moderately high social weight, where scenario C becomes the preferred option. A change in the weight of the environmental aspect does not change the rank order of the scenarios.

The three expert case studies carried out also show that the ranking of the scenarios remains the same under each expert's preference, with scenario D the preferred option, followed by scenario C, then B and finally, A. The results of these case studies display variable sensitivity; the techno-economic and social perspectives case studies are relatively insensitive to a change in weight on the aspects of sustainability. The rank order only changes in the techno-economic expert case study when the social weight is increased significantly, where scenario C becomes the preferred option, followed by scenarios D, B, then A. Similarly, the rank order for the social perspective case study also only changes when the weight of one aspect of sustainability (in this case, techno-economic) is increased very significantly. When this is carried out, scenario A becomes the preferred option, followed by scenarios D, B and C. Conversely, the environmental perspective expert case study exhibits increased sensitivity; the rank order of preference for the scenarios changes when the weight of all aspects of sustainability are changed. In this case, a very high weight on the techno-economic aspect would induce a rank change of the scenarios to A as the preferred option, followed by scenarios D, B and C. A very low weight on the environmental aspects would change the order of preference of scenarios A and B, with scenario A being preferable to B. Finally, a high weight on the social aspect would make scenario C the preferred option, followed by scenarios D, B and A. Therefore, even in the case study taking into account the environmental perspective of an expert stakeholder, where the rank order can change under varying weights of each aspect of sustainability, the rank order is still very robust – a complete change in opinion on the importance of the aspects of sustainability would need to occur in order to facilitate these changes.

However, the rank order of the scenarios changes significantly when feeling on the range of electricity options within each scenario is taken into account. In the three case studies, scenario C becomes the preferred option under the techno-economic and environmental perspective, and scenario B becomes the preferred option under the social perspective. In the case of scenario C, the preference here is due to favourable opinion of both experts on offshore wind and solar power, which are at their highest combined penetration within this scenario. Favourability on nuclear power is moderate to low in the case of all experts, meaning that scenario D never dominates as it contains a high proportion of nuclear power (60%). Scenario B is preferred when taking into account the opinion on the technologies from the social perspective. In this case, the expert has very favourable opinion on solar power, which dominates in scenario B and moderately favourable opinion on offshore wind and nuclear power, meaning that scenario C is ranked second under this perspective.

The average public preferences for the sustainability indicators and aspects display the same ranking of the scenarios as the expert case studies: D, C, B and A. These results do also show limited sensitivity; the rank order only changes when a very high weight is placed on techno-economic aspects (rank order = A, D, B, C), a moderately high weight is placed on social aspects (rank order = C, D, B, A) and a very low weight is placed on environmental aspects (rank order = C, D, B, A).

Again, the ranking of the scenarios only changes significantly when feelings towards electricity generation options are taken into account. The public favourability for solar power makes scenario B the preferred option, followed by scenario C which also has a relatively high penetration of solar power and a high penetration of wind power, which is also favoured by the public. Scenario D is third (opinion on nuclear power is moderate) and scenario A is the last in rank due to the unfavourable opinions on fossil fuel technologies.

The results for the expert and public analyses display similarity based on both the opinion on the sustainability indicators and aspects and based on electricity technologies preferred. These results show that scenario D is robustly preferred when taking into account the sustainability impacts of the scenarios within all case studies, but that scenario C (in the case of the techno-economic and environmental expert case studies) and scenario B (in the case of the social expert case study and public weighting) are the preferred option when taking into account opinion, or feeling towards the electricity options.

The following and final chapter of this thesis presents the finalised conclusions of the work carried out and also proposes future work based on those findings.

9 Conclusions and Recommendations for Future Work

This research has focussed on the application of a multi-criteria decision-support framework for the sustainability assessment of nuclear power in the UK compared to other electricity options and within a variety of future electricity scenarios. The framework has taken into account techno-economic, environmental and social aspects of sustainability and stakeholder opinions on these through the use of multi-criteria decision-analysis. Although the focus has been on nuclear power, other electricity options have also been considered. This thesis may be used for strategic decision-making in the context of nuclear power sustainability, in addition to the other technologies considered. However, different decision makers and stakeholders may wish to take into account a smaller number of issues, or focus specifically on different aspects of sustainability. In addition, individual stakeholders and stakeholders not currently considered in this thesis may wish to explore the sustainability of certain technologies and/or electricity scenarios using only their own preference weights. Furthermore, decision makers and stakeholders using this thesis in the future may wish to consider emerging technologies. In these cases, further modelling of new technologies and/or additional stakeholder weights would be needed.

The objectives of this research have been met in that:

- a methodology for stakeholder engagement has been developed and applied to determine the most sustainable electricity options and future electricity scenarios for different stakeholder (public and expert) opinions;
- sustainability assessment of future nuclear power options and coal carbon capture and storage up to the year 2070 has been carried out;
- sustainability assessment has been carried out of different electricity scenarios for the UK up to the year 2070; and
- multi-criteria decision-analysis of the findings of the sustainability assessments taking into account stakeholder preferences has been undertaken using a number of case studies.

The main conclusions from this work are summarised below. This is followed by recommendations for future work.

9.1 Conclusions

The conclusions drawn from this work are listed below following the headings of several of the chapters within this thesis.

9.1.1 Expert stakeholder consultation

9.1.1.1 First stage consultation

- Based on average ratings of the indicators, the first stage expert stakeholder feedback showed that the indicators were important and therefore valid measures in assessing the sustainability of nuclear power compared to other energy options (with an average rating of 2.9 out of a maximum 4, with a score of one representing ‘unimportant’ and a score of 4 representing ‘very important’).
- The technical group of indicators were rated as the most important (based on average ratings), with a score of 2.97 out of 4. This was followed by environmental indicators (2.93), social (2.89) and finally, economic indicators (2.84).
- The first stage consultation showed that stakeholders thought the most important indicators to use when assessing the sustainability of nuclear and other energy options to be: lifetime of global fuel reserves at current extraction rates; greenhouse gas emissions; radioactive waste production; total production costs; fatalities from large accidents; active waste management required; and security of fuel supply, which all received average scores of over 3.5 out of 4.
- The least important indicators determined during the first stage expert consultation were considered to be percentage of sites with fly-in, fly-out operations and all other local impact indicators (proportion of management hired from the local community, involvement in local community projects, proportion spent on local suppliers and direct payments to local communities).
- Feedback from the first stage consultation showed that experts wished the following additional indicators to be considered within the decision-support framework:
    - Technical – nuclear supply chain capability and capability of the transmission grid;
    - Economic – carbon price and subsidies, return on investment and economic risk;

  - Environmental – radiation dose to the environment and localised environmental impacts
  - Social – skills and expertise, waste repository needed for high level nuclear waste, risk of terrorism and public opinion.

Several of these issues have been addressed as part of the work carried out within this thesis, namely: public opinion on sustainability indicators, issues and electricity options (chapter 5) and skills, waste repository and risk of terrorism as part of the IAEA's evaluation of nuclear capability (chapter 6).

9.1.1.2 Second stage consultation

The results of the second stage consultation, which involved 45 expert stakeholders suggested that:

- Hydroelectric power is the most favourable electricity option overall, followed by solar power and then wind power.
- The least favourable method of electricity generation is oil-fired power, followed by coal- and then gas-fired power.
- The electricity options which display the most controversy due to split in favourable and unfavourable opinion are coal- and gas-fired power and nuclear power.
- There is a good agreement of the opinions related to the unfavourability of oil-fired power and the favourability of hydroelectric and biomass-fired power.
- Based on average rating of indicators, expert stakeholders rate the techno-economic indicators the most important to consider in a sustainability assessment (with n average median rating of 62.8 out of 100), followed by social (60.4) and then environmental indicators (56.4).
- Of all the indicators, the expert stakeholders show most consensus on the importance of measuring greenhouse gas emissions from electricity options and scenarios.

9.1.2 Public consultation

9.1.2.1 First stage consultation

- The public consulted as part of this survey identified solar, then hydroelectric and wind power, respectively, as the most favourable options for power generation in the UK.
- The least favourable option for the public overall is oil-fired power. Coal-fired power is the second least favourable option and gas-fired power is the third least favourable option.
- The most important sustainability indicators for the public when comparing energy options in the UK are (in order of importance): water contamination from toxic substances, land contamination from toxic substances and greenhouse gas emissions.
- The least important sustainability indicator is cost of electricity, followed by fuel imports avoided, and finally acid rain.
- The public opinion on nuclear power appears to have remained unchanged (43% in favour and 39% against), even after the Fukushima disaster.

9.1.2.2 Second stage consultation

- The results of the 2nd stage consultation showed that UK public opinion on electricity options has remained unchanged over the time that the first and second surveys took place suggesting robustness of the results.
- The electricity options for which there is least agreement among the public are nuclear and solar power. On the other hand, there is high consensus on the unfavourability of oil-fired power.
- The environmental indicators are considered by the public the most important and there is most agreement across these indicators on their importance. Techno-economic indicators are considered the second most important set, and social indicators are considered the least important set and display the greatest spread in opinion.
- Global warming is rated as a very important issue by the majority of the public consulted (there is least spread in opinion on this indicator).

Overall, the results suggest that the expert and public opinion on different electricity technologies and sustainability aspects broadly concurs.

9.1.3 IAEA Indicators for Nuclear Power Development (INPD)

- Policy projections show that although primary energy demand is likely to fall in the coming years to 2025, power generation will increase, with the additional demand to be comprised of gas-fired power and renewable technologies. Nuclear power will not increase on the grid until after 2020 due to its long lead-in times.
- Nuclear power can play a large part in low carbon power provision, although caveats to its implementation exist and include: provision of a high level waste repository; and uranium supply from outside the UK (which may be sensitive to geopolitical tension).
- The current economic situation in the UK leaves little capital investment from the Government for new nuclear power provision. This is due to low levels of growth and expected low growth over the coming five years and current economic vulnerability. This means that new nuclear power projects must now be privately funded.
- As energy provision makes the largest contribution to UK carbon emissions overall, provision of low carbon energy can significantly reduce the UK's carbon footprint.
- Trade-offs of environmental impacts across energy options is needed in order to determine which energy options should be implemented in the UK's national energy policy.
- A generational gap in skills and expertise of nuclear power specifically and engineering generally may leave the UK vulnerable in management of a nuclear power programme.
- Nuclear power displays relatively low impacts in regard to accident fatalities, but public opinion on nuclear power is mixed, meaning that its implementation could be sensitive to negative public opinion in the future.

9.1.4 Sustainability assessment of future electricity options

- Techno-economic indicators: Both AP1000 and EPR reactors display good operability performance and levelised costs over the whole life cycle. The EFR performs relatively badly under the operability indicators, with values for capacity and availability factors at 7.8 and 9%, respectively, although the EFR performs well under the lifetime of fuel reserves, fuel price sensitivity and financial incentives. Coal CCS is an expensive technology, having the highest total levelised costs overall, compared to the other technologies considered here. However, CCS performs well for the technical and economic dispatchability indicators.
- Environmental indicators: The EFR has the lowest environmental impacts compared against the AP1000, EPR and coal CCS. Coal CCS performs relatively badly for all indicators, including GWP, where it exhibits values around 60 times higher than the AP1000 and EPR, and around 300 times higher than the EFR.
- Social indicators: Total employment is highest for coal CCS, whilst direct employment for the four technologies is relatively similar. The EFR performs well for fuel storage capability and diversity of fuel supply. Coal CCS is the best option for human health impacts from radiation and total employment. The AP1000 and EPR reactors do not display the best performance under any of the indicators, although the do outperform the coal CCS option under several indicators (worker injuries, large accident fatalities, fossil fuel avoided and CO_2 storage) together with the EFR.
- MCDA carried out on the technologies shows that the EFR is the preferred option overall (scoring of 0.76), with the EPR in second place (scoring 0.7). This is closely followed by the AP1000 (0.68) and coal post-combustion CCS (0.28) is the least preferable option. These results display little sensitivity, with the overall sustainability ranking unaffected by changing of the preference weights.

9.1.5 Integrated sustainability assessment of future electricity scenarios for the UK

- Equal weighting of sustainability indicators and aspects shows that scenario D (low carbon with 59.5% nuclear power, 1.5% solar power and 39% wind power technologies) is the most sustainable future electricity scenario for the UK. The second most sustainable scenario is C (26% nuclear power, 48% wind power and

26% solar power), followed by scenario B (20% nuclear power, 20% wind power, 40% solar power and 20% coal CCS power). Finally, scenario A is the least preferable option (38% nuclear, 4% coal-fired power, 14% gas-fired power, 17% wind power and 27% coal CCS power).

- This ranking of the scenarios remains the same for most of expert stakeholder preferences and weightings of the sustainability indicators and aspects. However, the change in ranking is found for the following extreme conditions: when a moderately high weight (29-77%) is placed on social aspects of sustainability, scenario C becomes the preferable option; when a very high weight (96-97%) is placed on techno-economic aspects of sustainability, scenario A becomes the preferable option.
- When the scenarios are assessed based on expert opinion on the electricity options (rather than the sustainability indicators and aspects), scenario D is never the preferable option due to moderate to low expert preference for nuclear power, which dominates in this scenario with a 59.5% penetration.
- When considering the public opinion on the sustainability indicators and aspects, the same ranking of scenarios is found as in the expert case studies (preferable option is scenario D, followed by C, B and then A). This ranking changes for high techno-economic weighting (97%) when scenario A becomes preferred while scenario C becomes the best option for moderately high social weighting (67%) and/or low environmental weighting (3%).
- Public opinion on the electricity options places scenario B first in rank due to favourable public opinion of solar power (which dominates at 40% within this scenario). Scenario C is the second best option due to favourability of solar (26% penetration) and relatively high favourability of wind power (48% penetration). Scenario D is third - public preference for nuclear power is moderate and this scenario has high nuclear proportion (59.5%). Finally, scenario A is least preferable due to the unfavourable public opinion on coal- and gas-fired power.

9.2 Concluding Remarks

The multi-criteria decision-support framework for the assessment of the sustainability of nuclear power in UK future electricity mixes has been applied successfully within this work. The most sustainable electricity scenario option in the year 2070 under equal weighting is scenario D, which contains the highest proportion of nuclear power and a high penetration of offshore wind power. Scenario D dominates all other scenarios, including under the variety of public and expert preference weights placed on the sustainability indicators and sustainability pillars. It is only when preference weights are placed on the individual electricity options (as opposed to indicators) that scenario D is relegated to second or third place, by either scenario B or C. This indicates that stakeholder opinion, or ‘feeling’ towards nuclear power has a higher weighting than its actual sustainability impacts, and it is only when this is taken into account that nuclear power become less sustainable than the other electricity options considered in this work.

Therefore, the results from this research suggest that the ‘sustainability’ of different electricity options and scenarios is highly dependent on stakeholder preferences and priorities. Thus, for a successful future deployment of these options and implementation of energy policy measures, transparency of information on the impacts of electricity options is key in ensuring that stakeholder opinions are founded in the actual rather than the perceived impacts of these options. The methodologies employed in this thesis and the results generated are particularly applicable to decision makers on energy policy (specifically, government), as the findings highlight the need for open dialogue on the objective impacts of all electricity-generating technologies with the public and expert stakeholders. In this way, members of the public and other stakeholders may realise the actual impacts of the variety of technologies examined within this thesis. This is particularly relevant to nuclear power, which is especially controversial amongst some stakeholders and members of the public. In addition, when developing strategic plans for energy policy, decision makers may also anticipate potential controversies and use results in this thesis to determine what the impacts of specific electricity technologies and scenarios would be. Adverse impacts may then be planned for and mitigated where possible. Due to the long lead-in times for technologies such as nuclear power and coal carbon capture and storage, the results from this thesis will continue to be relevant over the next generation power plant new-build, especially as the work carried out as part of this PhD examines the potential impacts of various electricity technologies to 2070.

9.3 Recommendations for Future Work

The following are suggestions for future work based on the work carried out in this research:

- Further statistical analysis and investigation of the expert stakeholder and public questionnaire feedback should be carried in order to identify relationships between opinion on importance of the sustainability indicators; proximity to electricity-generating installations; and opinion on electricity-generating options, in addition to the more specific nuclear power issues. In this way, determination of opinion sensitivities amongst the public and experts can be made.
- Wider consultation of expert stakeholders in the nuclear and electricity generation sector would provide a broader range of views on the sustainability of nuclear power within a variety of electricity mixes.
- More robust and detailed LCA studies of future nuclear technologies.
- Data quality and uncertainty analyses for all the data used in this work to quantify the level of uncertainty for the results.

10 References

Afgan, N. H., Gobaisi, D. A., Carvalho, M. G. and Cumo, M. (1998). *Sustainable energy development.* International Renewable and Sustainable Energy Reviews **2(3):** 235-286.

Afgan, N. H. and Carvalho, M. G. (2002). *Multi-criteria assessment of new and renewable energy power plants.* Energy **27:** 739-755.

Afgan, N. H. and Carvalho, M. G. (2004). *Sustainability assessment of hydrogen energy systems.* International Journal of Hydrogen Energy **29:** 1327-1342.

Akella, A. K., Saini, R. P. and Sharma, M. P. (2009). *Social, economical and environmental impacts of renewable energy systems.* Renewable Energy **34:** 390-396.

Alberts, D. J. (2007). *Stakeholders or subject matter experts, who should be consulted?* Energy Policy **35**: 2336-2346.

ANA (2005). *Fast Reactor Technology: A Path to Long-Term Energy Sustainability.* American Nuclear Association, 2005. Available at: www.ans.org/pi/ps/docs/ps74.pdf

Anderson, K. L., Mander, S. L., Bows, A., Shackley, S., Agnolucci, P. and Ekins, P. (2008). *The Tyndall decarbonisation scenarios – Part II: Scenarios for a 60% reduction in the UK.* Energy Policy 36: 3764-3773.

Areva NP (2005). *EPR.* Available at: http://www.areva-np.com/common/liblocal/docs/Brochure/EPR_US_%20May%202005.pdf

Areva NP (2006). *Finish EPR Olkiluoto 3: The world's first third-generation reactor now under construction.* Available at: http://www.areva.com/news/liblocal/docs/FICHIERS%20PDF%20BR/BR-2006-06-05-01-EN.pdf

Areva NP and EDF (2007a). *Chapter 1:Introduction and General Description.* In: *The Pre-Construction Safety Report.* Available at: www.epr-reactor.co.uk

Areva NP and EDF (2007b). *Chapter 3:General Design and Safety Aspects.* In: *The Pre-Construction Safety Report.* Available at: www.epr-reactor.co.uk

Areva NP and EDF (2007c). *Chapter 11: Discharges and Waste: Chemical and Radiological.* In: *The Pre-Construction Safety Report.* Available at: www.epr-reactor.co.uk

Areva NP and EDF (2007d). *Chapter 20: Design Principles Related to Decommissioning.* In: *The Pre-Construction Safety Report.* Available at: www.epr-reactor.co.uk

Areva NP and EDF (2011). *Chapter 17: Compliance with ALARP Principle.* In: *The Pre-Construction Safety Report.* Available at: www.epr-reactor.co.uk

Areva NP and EDF (2012). *A cost effective reactor.* Available at: http://www.epr-reactor.co.uk/scripts/ssmod/publigen/content/templates/show.asp?P=90&L=EN&SYNC=Y

Azapagic, A. and Perdan, S. (2000). *Indicators of sustainable development for industry: A general framework.* Process Safety and Environmental Protection **78(4):** 243-261.

Azapagic, A. (2002). *Developing a framework for sustainable development indicators for the mining and minerals industry.* Journal of Cleaner Production **12**: 639-662.

Azapagic, A. and Perdan, S. (2003). *Managing Corporate Social Responsibility: Translating Theory into Business Practice.* Corporate Environmental Strategy: International Journal of Corporate Sustainability **10**: 97-108.

Azapagic, A. (2004). *Developing a framework for sustainable development indicators for the mining and minerals industry.* Journal of Cleaner Production **12:** 639-662.

Azapagic, A. and Perdan, S. (2005a). *An integrated sustainability decision-support framework Part I: Problem structuring.* International Journal of Sustainable Development & World Ecology **12**: 98-111.

Azapagic, A. and Perdan, S. (2005b). *An integrated sustainability decision-support framework Part II: Problem analysis.* International Journal of Sustainable Development & World Ecology **12**: 112-131.

Azapagic, A., Grimston, M., Anderson, K., Baker, K., Glynn, S., Howell, S., Kouloumpis, V., Perdan, S., Simpson, J., Stamford, L., Stoker, G., Thomas, P., Youds, L. (2011). *Assessing the sustainability of nuclear power in the UK: Summary findings and recommendations for policy and decision makers.* Available at: http://www.springsustainability.org/downloads/SPRIngReport.pdf

Balson, W. E., Welsh, J. L., Wilson, D. S. (1992). *Using decision analysis and risk analysis to manage utility environmental risk.* Interfaces **22(6):** 126–139.

Bartzis, J., Ehrhardt, J., French, S., Lochard, J., Morrey, M., Papamichail, K. N., Sinkko, K. A. and Sohier, A. (2000). *RODOS: Decision Support for Nuclear Emergencies.* In: Decision Making: Recent Developments and Worldwide Applications. The Netherlands, Kluwer Academic Publishers.

BBC, 2008 January. UK nuclear power: The contenders. Thursday, January 10th, 2008. Available at: http://news.bbc.co.uk/1/hi/sci/tech/5165182.stm

BBC, 2010 July. *Budget cuts caution on UK nuclear waste plan.* Available at: http://www.bbc.co.uk/news/10528937

BBC, 2010 October. Nuclear power: Eight sites identified for future plants. Monday, October 18th, 2010. Available at: http://www.bbc.co.uk/news/uk-politics-11564152

BBC, 2012a. RWE and E.On halt UK nuclear plans at Wylfa and Oldbury. Thursday, March 29th, 2012. Available at: http://www.bbc.co.uk/news/world-17546420

BBC, 2012b. Is the UK's nuclear future in jeopardy? Thursday, March 29th, 2012. Available at: http://www.bbc.co.uk/news/business-17550282

BBC, 2012c. Work on Dounreay's Shaft to be Sped Up. Tuesday, May 15th, 2012. Available at: http://www.bbc.co.uk/news/uk-scotland-highlands-islands-18063558

Begic, F. and Afgan, N. H. (2007). *Sustainability assessment tool for the decision making in selection of energy system – Bosnian case.* Energy **32:** 1979-1985.

Bellona, 2008. *How to Combat Global Warming.* Bellona Foundation, 2008. Report for the CC8 Conference, Oslo. Available at: http://www.bellona.org/filearchive/fil_Bellona_CC8_Report_-_Final_version_-_30_mai.pdf

Belton, V. and Stewart, T.J. (2002). Multiple Criteria Decision Analysis: An Integrated Approach. *New York: Kluwer Academic; 2002:372.*

BERR (2008). *Meeting the Energy Challenge – A White Paper on Nuclear Power. Cm 7296.* Department for Business Enterprise and Regulatory reform. Norwich, The Stationary Office.

Bloomberg (2009). French Nuclear Watchdog Says EDF Has Problems With Flamanville Nuclear Liner. Monday, August 30th, 2010. Available at: http://www.bloomberg.com/news/2010-08-30/edf-has-welding-problems-at-flamanville-epr-reactor-french-watchdog-says.html

Blunt, M. (2010). Grantham Institute for Climate Change Briefing paper No 4. December 2010. Available at: https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Briefing%20Paper%204.pdf

BNFL (2004). *BNFL National Stakeholder Dialogue.* The Environmental Council. Available at: http://www.the-environment-council.org.uk/

Bohringer, C., Hoffmann, T. and Vogele, S. (2002). *The cost of phasing out nuclear power: a quantitative assessment of alternative scenarios for Germany.* Energy Economics **24:** 469-490.

British Energy (2008). *Environmental Product Declaration of Electricity from Sizewell B Nuclear Power Station – Technical Report.* AEA Energy & Environment, London.

Brunsting, S., Upham, P., Dutschke, E., De Best Waldhober, M., Oltra, C., Desbarats, J., Riesch, H. and Reiner, D. (2011). *Communicating CCS: Applying communications theory to public perceptions of carbon capture and storage.* International Journal of Greenhouse Gas Control **5**(6): 1651-1662.

Bryson, J. M. (2004). *What to do when stakeholders matter.* Public Management Review **6(1):** 21-53.

Buchholz, T. S., Volk, T. A. and Luzadis, V. A. (2007). *A participatory systems approach to modelling social, economic and ecological components of bioenergy.* Energy Policy **35**: 6084-6094.

Burgherr, P., Hirschberg, S., and Cazzoli, E (2008). *Final report on quantification of risk indicators for sustainability assessment of future electricity supply options*. In Deliverable D7.1 — RS 2b. 2008, NEEDS (New Energy Externalities Development for Sustainability).

Burton, J. and Hubacek, H. (2007). *Is small beautiful? A multicriteria assessment of small-scale energy technology applications in local governments.* Energy Policy **35**: 6402-6412.

Cao, Y., Pawłowski, A. (2013). *Life cycle assessment of two emerging sewage sludge-to-energy systems: Evaluating energy and greenhouse gas emissions implications.* Bioresource Technology, **127**: 81-91.

CCSA, 2012. *CCS Project Proposals. Current UK Project Proposals.* Carbon Capture and Storage Association, 2012. Available at: http://www.ccsassociation.org/why-ccs/ccs-projects/current-projects/

CML (2002). *Life cycle assessment. An operational guide to the ISO standards.* In: *Guinee Jeroen, editor. Centrum Milieukunde Leiden (CML)*. Kluwer, Dordrecht, NL: Leiden University, NL, 2002.

Coello Coello, C. A., Hernandez Aguirre, A. and Zitzler, E. (2006). *Evolutionary multi-objective optimization.* European Journal of Operational Research **181**: 1617-1619.

Cohen, S. M., Rochelle, G. T. and Webber, M. E. (2012). *Optimizing post-combustion CO_2 capture in response to volatile electricity prices.* International Journal of Greenhouse Gas Control **8** 180-195.

Conservative Party, 2010. *Invitation to Join the Government of Britain*.

Cormos, C.C. (2010). *Integrated assessment of IGCC power generation technology with carbon capture and storage (CCS).* Energy **42** 434-445.

Corner, A., Venables, D., Spence, A., Poortinga, W., Demski, C. and Pidgeon, N. (2011). *Nuclear power, climate change and energy security: Exploring British public attitudes.* Energy Policy **39(9)**: 4823-483.

Corner, J. L. and Kirkwood, C. W. (1991). *Decision analysis applications in the operations research literature, 1970-1989.* Operations Research **39(2):** 206-219.

CoRWM (2005). *CoRWM's Radioactive Waste and Materials Inventory – Jul 2005.* Committee on Radioactive on Radioactive Waste Management. Document no. 1279. CoRWM, London.

CoRWM (2006). *Managing our radioactive Waste Safely: CoRWM's recommendations to Government.* CoRWM DOC 700. Available at: http://www.corwm.org.uk/default.aspx

CoRWM (2009a). *Interim Storage of Higher Activity Wastes and the Management of Spent Fuels, Plutonium and Uranium.* CoRWM DOC 2500. Available at: http://www.corwm.org.uk/default.aspx

CoRWM (2009b). *Geological Disposal of Higher Activity Radioactive Wastes.* CoRWM DOC 2550. Available at: http://www.corwm.org.uk/default.aspx

CoRWM (2009c). *Report on National Research and Development for Interim Storage and Geological Disposal of Higher Activity radioactive Wastes, and management of Nuclear Materials.* CoRWM DOC 2543. Available at: http://www.corwm.org.uk/default.aspx

Cuppen, E., Breukers, S., Hisschemoller, M. and Bergsma, E. (2010) *Q methodology to select participants for a stakeholder dialogue on energy options from biomass in the Netherlands.* Ecological Economics **69**: 579-591.

DECC (2009)*. The UK Low Carbon Transition Plan – National strategy for climate and energy*. Department of Energy and Climate Change. Norwich, The Stationary Office.

DECC (2010). *Energy Act 2010.* Department of Energy and Climate Change. Norwich, The Stationary Office.

DECC (2011). *The Carbon Plan.* Department of Energy and Climate Change. Available at: http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/carbon-plan/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf

DECC (2012a). *Energy Bill. Cm 8362.* Department of Energy and Climate Change. Norwich, The Stationary Office.

DECC, 2012b. CCS Competition Launched as Government Sets Out Long Term Plans. Tuesday, April 3rd, 2012. Available at: http://www.decc.gov.uk/en/content/cms/news/pn12_040/pn12_040.aspx

DECC (2012c). *CCS Roadmap. Supporting Deployment of Carbon Capture and Storage in the UK. URN 12D/016*. Department of Energy and Climate Change. Available at: http://www.decc.gov.uk/assets/decc/11/cutting-emissions/carbon-capture-storage/4899-the-ccs-roadmap.pdf

DECC (2012d). *Digest of United Kingdom Energy Statistics 2012.* Department of Energy and Climate Change, 2012. Available at: http://www.decc.gov.uk/assets/decc/11/stats/publications/dukes/5949-dukes-2012-exc-cover.pdf

DECC (2012e). *2011 UK Greenhouse Gas Emissions*. A National Statistics Publication. London, The Stationary Office.

DEFRA (1999). *A Better Quality of Life: A Strategy for Sustainable development for the United Kingdom.* Department of Food and Rural Affairs.

DEFRA (2005). *Securing the Future – Delivering UK Sustainable Development Strategy.* Department of Food and Rural Affairs. Norwich, The Stationary Office.

Desideri, U., Proietti, S., Zepparelli, F., Sdringola, P., Bini, S. (2012). *Life Cycle Assessment of a ground-mounted 1778 kWp photovoltaic plant and comparison with traditional energy production systems*. Applied Energy, **97**: 930-943

DfE (2011 November). *Education and Training Statistics for the United Kingdom: 2012.* Available at: http://www.education.gov.uk/rsgateway/DB/VOL/v001045/index.shtml

Dinca, C., Badea, A., Rousseaux, P. and Apostol, T. (2007). *A multi-criteria approach to evaluate the natural gas energy systems.* Energy Policy **35:** 5754-5765.

Dincer, I. (2000). *Renewable energy and sustainable development: a crucial review.* Renewable and Sustainable Energy Reviews **4:** 157-175.

DTI (2003). *Our energy future – creating a low carbon economy.* Department of Trade and Industry, Feb 2003.

DTI (2006a). *Responses to 'Our Energy Challenge' Consultation.* Department of Trade and Industry, Jan 2006.

DTI (2006b). *The Energy Challenge.* Department of Trade and Industry, July 2006.

DTI (2007). *Meeting the Energy Challenge.* Department of Trade and Industry, July 2006.

EcoInvent (2010). EcoInvent Centre, 2010. Available at: http://www.ecoinvent.org/

Eden, C. and Ackerman, F. (1998). *Making Strategy: The Journey of Strategic Management.* London, Sage Publications.

Elghali, L., Clift, R., Sinclair, P., Panoutsou, C. and Bauen, A. (2007). *Developing a sustainability framework for the assessment of bioenergy systems.* Energy Policy 35: 6075-6083.

Fernandez-Sanchez, G. and Rodriguez-Lopez, F (2010). *A methodology to identify sustainability indicators in construction project management – Application to infrastructure projects in Spain.* Ecological Indicators **10(6):** 1193-1201.

Figueroa, J. D., Fout, T. et al. (2008). *Advances in CO2 capture technology--The U.S. Department of Energy's Carbon Sequestration Program*. International Journal of Greenhouse Gas Control **2**(1): 9-20.

FoE & GfK NOP (2011). Post Fukushima Public Perception of Nuclear Power Poll. Accessed through request to Friends of the Earth.

Fraser, E. D. G., Dougill, A. J., Mabee, W. E., Reed, M. and McAlpine, P. (2006). *Bottom up and top down: Analysis of participatory processes for sustainability indicator identification as a pathway to community empowerment and sustainable environmental management.* Journal of Environmental Management **78**: 114-127.

French, S. and Geldermann, J. (2005). *The varied contexts of environmental decision problems and their implications for decision support.* Environmental Science and Policy **8:** 378-391.

Gamboa, G. and Munda, G. (2007). *The problem of windfarm location: A social multi-criteria evaluation framework.* Energy Policy **35:** 1564-1583.

Garcez, C. A. G. and de Souza Vianna, J. N. (2009). *Brazilian Biodiesel Policy: Social and Environmental Considerations of Sustainability.* Energy **34:** 645-654.

Geels, F.W., Elzen, B., Green, K., (2004). System Innovations and Transitions to Sustainability, in: Geels, F.W., Elzen, B., Green, K. (Eds.), *System Innovation and the Transition to Sustainability*. Edward Elgar Publishing Limited, Cheltenham.

Glaser, B. G. and Strauss, A. L. (1967). *The discovery of grounded theory: strategies for qualitative research.* Chicago. Aldine.

Graham DJ and Midgley NG. 2000. Graphical representation of particle shape using triangular diagrams: an Excel spread sheet method. *Earth Surface Processes and Landforms* **25**(13): 1473-1477.

Granat, J. and Makowski, M. (2006). *Multicriteria methodology for the NEEDS project.* International Institute for Applied Systems Analysis, Laxenburg, Austria, August 2006. Available at: http://www.needs-project.org/docs/results/RS2b/RS2b_T9.2.pdf

GREA (2010). *Renewable Energies and Base Load Power Plants: Are They Compatible?* German Renewable Energies Agency, Issue 35, June 2010.

Greenhalgh, C. and Azapagic, A. (2009). *Review of Drivers and Barriers for Nuclear Power in the UK.* Environmental Science and Policy **12**: 1052-1067.

Greenpeace (2005). *The real cost of nuclear electricity production: Critical Comments on NEA-IEA 'Projected Costs of Electricity Production'.* Greenpeace International, March 2005.

GRI (2000). *Sustainability reporting guidelines on economic, environmental and social performance.* G3.1, Global Reporting Initiative, 2011.

Guinee, J. B., Gorree, M., Heijungs, R., Hupped, G., Kleijn, R., van Oers, L., Wegener, S. A., Udo de Haes, H. A., Bruijn, J. and Duin, V. R. (2001). *Life Cycle Assessment: an operational guide to the ISO standards*. Kluwer Academic Publishers, D. (Ed.) The Netherlands. Centre for Environmental Science, The University of Leiden.

Gunningham, N. and Sinclair, D. (2002). *Leaders & Laggards: Next-Generation Environmental Regulation*, Greenleaf Publishing.

Ho, M. W., Cherry, B., Burcher, S. and Saunders, P., 2009. *Green Energies 100% Renewables by 2050.* Institute of Science in Society.

Holloway, S. (2008). *Storage capacity and containment issues for carbon dioxide capture and geological storage on the UK continental shelf*. Proc. IMechE **223**(A:1): 239-248.

House of Lords (2000). *Science and Society: Select Committee on Science and Technology Third Report.* London.

van den Hove, S. (2000). *Participatory approaches to environmental policy making: the European Commission Climate Policy Process as a case study.* Ecological Economics **33:** 457-472.

HSE (2008). *Report of the Public Involvement Process associated with the Generic Design Assessment of New Nuclear Reactor Designs.* Health and Safety Executive, March 2008. Available at: http://www.hse.gov.uk/newreactors/reports/publicinvolvment.pdf

HSE (2009a). *Generic Design Assessment – New Civil Reactor Build. Step 3 Reactor Chemistry Assessment of the Westinghouse AP1000.* Assessment Report No. 09/035. Health and Safety Executive. Available at: http://www.hse.gov.uk/newreactors/reports/step3-ap1000-reactor-chemistry-report.pdf

HSE (2009b). *Generic Design Assessment – New Civil Reactor Build. Step 3 Radioactive Waste and Decommissioning Assessment of the Westinghouse AP1000.* Assessment Report No. 09/023. Health and Safety Executive. Available at:

http://www.hse.gov.uk/newreactors/reports/step3-ap1000-radioactive-waste-decommissioning-assessment.pdf

HSE (2011). *Generic Design Assessment Progress Report Reporting Period 1st January 2011 – 31 March 2011.* Health and Safety Executive. Available at: http://www.hse.gov.uk/newreactors/reports/gda-q1-11.pdf

HSE (2012). *Generic Design Assessment Progress Report Reporting Period 1st January 2012 – 31 March 2012.* Health and Safety Executive. Available at: http://www.hse.gov.uk/newreactors/reports/gda-q1-12.pdf

I-Nuclear, 2012. DECC: Requirement for EDF to sell Bradwell land for new nuclear still in force. Thursday, March 8th, 2012. Available at: http://www.i-nuclear.com/2012/03/08/decc-requirement-for-edf-to-sell-bradwell-land-for-new-nuclear-still-in-force/

IAEA (1970). INFCIRC/140. *Treaty on the Non-Proliferation of Nuclear Weapons*.

IAEA (1972). INFCIRC/153. *The Structure and Contents of Agreements Between The Agency and States Required in Connection with Treaty on the Non-Proliferation of Nuclear Weapons.*

IAEA (2002). *Operational and decommissioning experience with fast reactors.* Proceedings of a technical meeting held in Cadarache, France, 11–15 March 2002. Available at: http://www-pub.iaea.org/MTCD/publications/PDF/te_1405_web.pdf

IAEA, UNDESA, IEA, Eurostat and EEA (2005). *Energy indicators for sustainable development: guidelines and methodologies.*

IAEA (2006). Chernobyl’s Legacy: Health, Environmental and Socio-Economic Impacts. April, 2006. Available at: http://www.iaea.org/Publications/Booklets/Chernobyl/chernobyl.pdf

IAEA (2012a). Global Uranium Supply Ensured for Long Term, New Report Shows. Thursday, July 26th, 2012. Available at: http://www.iaea.org/newscenter/pressreleases/2012/prn201219.html

IAEA (2012b). Power reactor information system. Available from: http://www.iaea.org/pris, 2012.

IEA (2011a). *CO_2 Emissions from Fuel Combustion.* International Energy Agency, 2011. Available at: http://www.iea.org/co2highlights/CO2highlights.pdf

IEA (2011b). *Cost and Performance of Carbon Dioxide Capture from Power Generation*. International Energy Agency, 2011. Available at: http://www.iea.org/papers/2011/costperf_ccs_powergen.pdf

IEA and NEA (2010). *Projected costs of generating electricity 2010 edition.* Paris: OECD Publications, 2010.

IEAGHG (2011). *Caprock systems for CO2 Geological Storage*. IEAGHG. **2011/01**.

IER, 2005. *ExternE, Externalities of Energy: Methodology 2005 Update. EUR 21951.* Institut für Energiewirtschaft und Rationelle Energieanwendung, 2005. Available at: http://www.externe.info/

International Monetary Fund (2012 October). *World Economic Outlook Database.* Available at: http://www.imf.org/external/pubs/ft/weo/2012/02/weodata/index.aspx

IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge, Cambridge University Press.

IPFM (2010). *Fast Breeder Reactor Programs: History and Status.* International Panel on Fissile Materials, 2010. Available at: http://fissilematerials.org/library/rr08.pdf

Ipsos-Mori (2011a). Strong global opposition towards nuclear power. Available at http://www.ipsos-mori.com/researchpublications/researcharchive/2817/Strong-global-opposition-towards-nuclear-power.aspx

Ipsos MORI, (2011b). *Nuclear Update Dec 2011*. Available at: http://www.ipsos-mori.com/researchpublications/researcharchive/2903/Nuclear-Energy-Update-Poll.aspx, last accessed September 2012.

ISO (2006). ISO 14040 – Environmental management – life cycle assessment – principles and framework. Geneva, 2006.

ISO (2006). ISO 14044 – Environmental management – life cycle assessment – requirements and guidelines. Geneva, 2006.

Jordan, A., Wurzel, R. K. W. and Zito, A. R. (2003). *'New' Instruments of Environmental Governance? National Experiences and Prospects*.

Jovanovic, M., Afgan, N., Radovanovic, P. and Stevanovic, V. (2009). *Sustainable development of the Belgrade energy system*. Energy **34:** 532-539.

Juanico, L. E., Florido, P. C. and Bergallo, J. E. (2002). *Probabilistic model for the economic evaluation of nuclear projects.* Nuclear Engineering and Design **211:** 237-244.

Keefer, D. L, Kirkwood, C. W., Corner, J. L. (2004). *Perspectives on Decision Analysis Applications, 1990-2001.* Decision Analysis **1(1):** 4-22.

Kelly, K.A., McManus, M.C., Hammond, G.P. (2012). *An energy and carbon life cycle assessment of tidal power case study: The proposed Cardiff–Weston severn barrage scheme.* Energy, **44(1)**: 692-701.

Komendantova, N., Patt, A., Barras, L. And Battaglini, A. (2012). *Perception of risks in renewable energy projects: The case of concentrated solar power in North Africa*. Energy Policy, **40**: 103-109.

Kone, A. C. and Buke, T. (2007). *An Analytical Network Process (ANP) evaluation of alternative fuels for electricity generation in Turkey.* Energy Policy **35**: 5220-5228.

Korre, A., Nie, Z. and Durucan, S. (2010). *Life cycle modelling of fossil fuel power generation with post-combustion CO_2 capture.* International Journal of Greenhouse Gas Control **4** 289-300.

Kouloumpis, V., Stamford, L. and Azapagic, A. (2012). Energy Technologies Life Cycle Assessment (ETLCA). Available at: http://www.springsustainability.org

Kowalski, K., Stagl, S., Madlener, R. and Omann, I. (2009). *Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis.* European Journal of Operational Research **197:** 1064-1074. Available at: http://www.project-artemis.net/index.html

Kunsch, P. L. and Fortemps, P. (2002). *A fuzzy decision support system for the economic calculus in radioactive waste management.* Information Sciences **142:** 103-116.

Liberal Democrats, 2010. *Climate Change and Energy Policy Briefing Document*.

Madlener, R., Stagl, S. (2005). *Sustainability-guided promotion of renewable electricity generation.* Ecological Economics **53(2)**: 147-167.

Madlener, R., Kowalski, K., Stagl, S. (2007). *New ways for an integrated valuation of national energy scenarios: The case of renewable energy use in Austria.* Energy Policy **35(12):** 6060–6074.

Madlener, R., Antunes, C. H. and Dias, L. C. (2009). *Assessing the performance of biogas plants with multi-criteria data envelopment analysis.* European Journal of Operational Research **197(3)**: 1084-1094.

Mander, S. L., Bows, A., Anderson, K. L., Shackley, S., Agnolucci, P. and Ekins, P. (2008). *The Tyndall decarbonisation scenarios – Part I: Devlopment of a backcasting methodology with stakeholder participation.* Energy Policy **36:** 3754-3763.

May, J. R. and Brennan, D. J. (2006). *Sustainability Assessment of Australian Electricity Generation.* Process Safety and Environmental Protection **84(B2):** 131-142.

McDowell, W. and Eames, M. (2007). *Towards a sustainable hydrogen economy: A multi-criteria sustainability appraisal of competing hydrogen futures.* International Journal of Hydrogen Energy **32:** 4611-4626.

Mizuo, J. (2008). *The social responsibility of nuclear energy.* Progress in Nuclear Energy **50:** 694-699.

Mog, J. M. (2004). *Struggling with Sustainability – A Comparative Framework for Evaluating Sustainable Development Programs.* World Development **32(12)**: 2139-2160.

Mott MacDonald (2010). UK Electricity Generation Costs Update. Brighton. Mott MacDonald, June 2010.

Munda, G. (1995). Multicriteria Evaluation in a Fuzzy Environment: Theory and Applications in Ecological Economics. *Physica-Verlag, Heidelberg.*

NCE (2009). EDF plays down concerns over Flamanville nuclear plant. Thursday, June 18th, 2009. Available at: http://www.nce.co.uk/news/energy/edf-plays-down-concerns-over-flamanville-nuclear-plant/5203617.article

NDA (2011). UK Radioactive Waste Inventory. Nuclear Decommissioning Authority. Department of Energy and Climate Change; Nuclear Decommissioning Authority: Didcot, UK.

NEA and IAEA (2009). Uranium 2009: resources, production and demand. Paris: OECD Publishing; 2010.

NEA (2010). *Public Attitudes to Nuclear Power.* Nuclear Energy Agency, 2010.

NEEDS (2005 Sept). *Establishment of social criteria for energy systems.* Available at: http://www.needs-project.org/index.php

NEEDS (2006 May). *The Role of Monetary Valuation of Externalities and Cost Benefit Analysis in Energy Policy Making.* Available at: http://www.needs-project.org/index.php

NEEDS (2006 June). *Requirement analysis for multicriteria analysis in NEEDS RS2b.* Available at: http://www.needs-project.org/index.php

NEEDS (2006 Aug 30). *Multicriteria methodology for the NEEDS project.* Available at: http://www.needs-project.org/index.php

NEEDS (2006 Aug). *Reporting and evaluation of the survey on the "externality concept".* Available at: http://www.needs-project.org/index.php

NEEDS (2007 August). *Environmental, economic and social criteria and indicators for sustainability assessment of energy technologies.* Available at: http://www.needs-project.org/index.php

NEEDS (2007 Dec). *Final report on technical data, costs and life cycle inventories of nuclear power plants.* Available at: http://www.needs-project.org/index.php

NEEDS (2008 Oct). *Final report on economic indicators for sustainability assessment of future electricity supply options.* Available at: http://www.needs-project.org/index.php

NEEDS (2008). *The NEEDS Life Cycle Inventory Database: The European reference life cycle inventory database of future electricity supply systems*. Cited 2013; Available from: http://www.needs-project.org/needswebdb/index.php

NEI (2009). Dounreay Fast Reactor celebrates fifty years. Tuesday, November 10th, 2009. Available at:
http://www.neimagazine.com/story.asp?sectionCode=132&storyCode=2054687

NEI (2011). EDF delays Flamanville 3 EPR project. Wednesday, July 20th, 2011. Available at:
http://www.neimagazine.com/story.asp?sectioncode=132&storyCode=2060192

New Scientist (2007). Nuclear industry revival hits roadblocks. Sunday, July 1st. 2007. Available at: http://www.newscientist.com/article/dn12167-nuclear-industry-revival-hits-roadblocks.html

NFLA (2006). *Responding to the DTI consultation on the policy framework for new nuclear build.* Nuclear Free Local Authorities, October 2006.

Nirex (2002). Identifying public concerns and perceived hazards for the phased disposal concept. March 2002. Available at: http://www.nda.gov.uk/documents/upload/Identifying-public-concerns-and-perceived-hazards-for-the-PDC-2002.pdf

OECD (2001), *Extended Producer Responsibility: A Guidance Manual for Governments,* OECD, Paris.

OECD (2011). *A Preliminary Assessment of Raw Material Inputs that Would be Required for Rapid Growth in Nuclear Generating Capacity.* Organisation for Economic Co-operation and Development, July 2011. Available at: http://www.oecd-nea.org/ndd/reports/2011/ndc-2011-15.pdf

Office for National Statistics (2012 September). *Government Deficit & Debt Under the Maastricht Treaty.* Available at: http://www.ons.gov.uk/ons/dcp171778_280559.pdf

Office for National Statistics (2012 Oct). *Statistical Bulletin: UK Trade.* Available at:
http://www.ons.gov.uk/ons/rel/uktrade/uk-trade/october-2012/stb-uk-trade--october-2012.html

Onat, N. and Bayar, H. (2010). *The sustainability indicators of power production systems.* Renewable and Sustainable Energy Reviews **14(9):** 3108-3115.

Parsons Brinckerhoff (2010). Powering the nation update 2010. Newcastle upon Tyne: Parsons Brinckerhoff; 2010.

Payne, J. W., Bettman, J. R. and Johnson, E. J. (1992). *Behavioural Decision research: A Constructive processing Perspective.* Annual Review of Psychology **43**: 87-131.

PE Europe (2003). *Software and database for life cycle engineering*. PE Europe GmbH and IKP University of Stuttgart, 2003.

Phillips, L. D. (1984). *A Theory of Requisite Decision Models*. Acta Psychologica **56**: 29-48.

Pidgeon, N. F, Turner, B. A. and Blockley, D. I. (1991). *The use of grounded theory for conceptual analysis in knowledge elicitation.* International Journal of Man-Machine Studies **35(2)**: 151-173.

Pietrapertosa, F., Cosmi, C., Macchiato, M., Salvia, M. and Cuomo, V. (2009). *Life Cycle Assessment, ExternE and Comprehensive Analysis for an integrated evaluation of the environmental impact of anthropogenic activities.* Renewable and Sustainable Energy Reviews **13:** 1039-1048.

Pohekar, S. D. and Ramachandran, M. (2004). *Application of multi-criteria decision making to sustainable energy planning – A review.* Renewable and Sustainable Energy Reviews **8:** 365-381.

PSI (2006 Feb). *Risk Assessment: selected results.* Available at: http://gabe.web.psi.ch/research/ra/ra_res.html#agg

Reuters (2011). Finland's Olkiluoto 3 reactor delayed to Aug '14. Wednesday, November 21st, 2011. Available at: http://www.reuters.com/article/2011/12/21/finland-olkiluoto-idUSL6E7NL2DI20111221

Roche, P. (2005). *Is nuclear power a solution to climate change?* no2nuclearpower.org.uk, April, 2005.

Roth, S., Hirschberg, S., Bauer, C., Burgherr, P., Dones, R., Heck, T., Schenler, W. (2009). *Sustainability of electricity supply technology portfolio.* Annals of Nuclear Energy **36** 409-416.

Say, N. P., Yucel, M. and Yilmazer, M. (2007). A computer-based system for environmental impact assessment (EIA) applications to energy power stations in Turkey: CEDINFO. Energy Policy **35(12):** 6395-6401.

Schulz, T. L. (2006). *Westinghouse AP1000 advanced passive plant.* Nuclear Engineering and Design **236** 1547-1557.

Shackley, S., Reiner, D., Upham, P., de Coninck, H., Sigurthorsson, G. and Anderson, J. (2009). *The acceptability of CO2 capture and storage (CCS) in Europe: An assessment of the key determining factors: Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation.* International Journal of Greenhouse Gas Control **3:** 344-356.

Simons, A. and Bauer, C. (2012). *Life cycle assessment of the European pressurised reactor and the influence of different fuel cycle strategies.* Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. Available at: http://pia.sagepub.com/content/early/2012/03/14/0957650912440549

Singh, R. K., Murty, H. R, Gupta, S. K and Dikshit, A. K. (2009). *An overview of sustainability assessment methodologies.* Ecological Indicators **9:** 189-212.

Singh, B., Stromman, A. H. and Hertwich, E. G. (2011). *Comparative impact assessment of CCS portfolio: Life cycle perspective.* Energy Procedia **4** 2486-2493.

Slovic, P. (1996). *Perception of Risk from Radiation.* Radiation Protection Dosimetry **68(3-4)**: 165-180.

Spangenberg, J.H. (2005). *Economic sustainability of the economy: concepts and indicators.* International Journal of Sustainable Development **8:** 47–64 (1/2).

Squarer, D., Schulenberg, T., Struwe, D., Oka, Y., Bittermann, D., Aksan, N., Maraczy, C., Kyrki-Rajamaki, R., Souyri, A. and Dumaz, P. (2003). *High performance light water reactor.* Nuclear Engineering and Design **221:** 167-180.

Stamford, L. and Azapagic, A. (2011). *Sustainability indicators for the assessment of nuclear power.* Energy **36** 6037-6057.

Stamford, L. and Azapagic, A. (2012). *Life cycle sustainability assessment of electricity options for the UK.* International Journal of Energy Research. Available online at: http://onlinelibrary.wiley.com/doi/10.1002/er.2962/pdf

Stamford, L. (2012). *Sustainability indicators for the assessment of electricity generation options in the UK.* PhD Thesis, The University of Manchester.

Steelman, T. and Ascher, W. (1997). *Public involvement methods in natural resource policy making: advantages, disadvantages and trade-offs.* Policy Sciences **30 (2):** 71-90.

Streimikiene, D., Simanaviciene, Z. and Kovaliov, R. (2009). *Corporate social responsibility for implementation of sustainable energy development in Baltic States.* Renewable and Sustainable Energy Reviews **13:** 813-824.

Styles, D. and Jones, M. B. (2008). *Life-cycle environmental and economic impacts of energy-crop fuel-chains: an integrated assessment of potential GHG avoidance in Ireland.* Environmental Science & Policy **11(4):** 294-306.

The Royal Academy of Engineering (2010). Nuclear Lessons Learned. Published by The Royal Academy of Engineering on behalf of Engineering the Future.

The Guardian, 2010. Conservative pre-election coal plant emissions promise goes up in smoke. Tuesday, November 23rd, 2010. Available at: http://www.guardian.co.uk/business/2010/nov/23/conservative-coal-plant-emissions-promise

The Guardian, 2011. Nuclear power plant accidents: listed and ranked since 1952. Friday, March 18th, 2011. Available at: http://www.guardian.co.uk/news/datablog/2011/mar/14/nuclear-power-plant-accidents-list-rank

The Guardian, 2012a. EDF puts Somerset nuclear plant on hold. Sunday, May 27th, 2012. Available at: http://www.guardian.co.uk/business/2012/may/27/edf-nuclear-delay

The Guardian, 2012b. UK nuclear plans 'need saving by David Cameron and Francois Hollande'. Tuesday, June 12th, 2012. Available at: http:/www.guardian.co.uk/environment/2012/jun/12/uk-nuclear-power-david-cameron?INTCMP=SRCH

The Guardian, 2012c. Gas rebranded as green energy by EU. Tuesday, May 29th, 2012. Available at: http://www.guardian.co.uk/environment/2012/may/29/gas-rebranded-green-energy-eu?INTCMP=SRCH

The Guardian, 2012d. Clean technology: what is the future of green energy? Tuesday, October 2nd, 2012. Available at: http://www.guardian.co.uk/sustainable-business/clean-technology-green-energy-future?INTCMP=SRCH

The Telegraph, 2011. Government set to invest £7 billion in low carbon technology. Sunday, July 10th, 2011. Available at: http://www.telegraph.co.uk/earth/greenpolitics/8628795/Goverment-set-to-invest-7-billion-in-low-carbon-technology.html

The University of Chicago (2004). *The Economic Future of Nuclear Power.* A study by The University of Chicago for the United States Department of Energy, 2004. Available at: http://www.ne.doe.gov/np2010/reports/NuclIndustryStudy-Summary.pdf

The World Bank (2011). *Governance Matters 2011: Worldwide Governance Indicators, 1996-2011.* Avalable at: http://info.worldbank.org/governance/wgi/sc_country.asp

The World Bank (2012). *GDP growth (annual %).* Available at: http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG

Tian, J. (2001). *Economic feasibility of heat supply from simple and safe nuclear plants.* Annals of Nuclear Energy **28:** 114-1150.

Tian, L. and Wang, Y. (2001). *A comparative economic assessment of a 200 MW nuclear heating reactor for seawater desalination by multi-effect distillation (MET).* Desalination **133:** 285-290.

Tian, L., Tang, Y. and Wang, Y. (2005). *Economic evaluation of seawater desalination for a nuclear heating reactor with multi-effect distillation.* Desalination **180:** 53-61.

Tokushige, K., Akimoto, K. And Tomoda, T. (2007). *Public perceptions on the acceptance of geological storage of carbon dioxide and information influencing the acceptance.* International Journal of Greenhouse Gas Control **1(1)**: 101-112.

Transparency International, 2011. Corruption perceptions index 2011 results. Available from: http://www.transparency.org/cpi2011/results

UKERC (2009). *Making the transition to a secure and low-carbon energy system: synthesis report.* UK Energy research centre, 2005. Available at: http://www.ukerc.ac.uk/Downloads/PDF/U/UKERCEnergy2050/0906UKERC2050.pdf

UN (2008). *Human Development Report 2008.* Available at: http://data.un.org/Data.aspx?d=GenderStat&f=inID%3A68

UNCED (1992). *Agenda 21, United Nations Conference on Environment and Development.* Rio de Janeiro, June 1992.

UNECE (1998 June). *Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters*. Aarhus, June 1998.

Walker, J. L. (1966). *A Critique of the Elitist Theory of Democracy*. The American Political Science Review **60(2)**: 285-295.

Westinghouse (2007a). *Chapter 4: Reactor.* In: *UK AP1000 Safety, Security and Environmental Report.* Westinghouse Electric Company. Available at: https://www.ukap1000application.com/ap1000_documentation.aspx

Westinghouse (2007b). *Chapter 20: Decommissioning.* In: *UK AP1000 Safety, Security and Environmental Report.* Westinghouse Electric Company. Available at: https://www.ukap1000application.com/ap1000_documentation.aspx

Westinghouse (2009). *Pre-Construction Safety Report.* Westinghouse Electric Company. Available at: https://www.ukap1000application.com/doc_pdf_library.aspx

Westinghouse (2010). *The AP1000 Nuclear Power Plant Global Experience and UK Prospects.* Presentation by Adrian Bull, Westinghouse. Available at: http://www.nuclearinst.com/uploads/Branch%20Presentations/The%20AP1000%20-%20A%20Bull%20-%2016th%20Nov%2010.pdf

Westinghouse (2011). *The AP1000 Environment Report.* Westinghouse Electric Company. Available at: https://www.ukap1000application.com/doc_pdf_library.aspx

Westinghouse (2012). *AP1000 at a glance.* Westinghouse Electric Company. Available at: http://ap1000.westinghousenuclear.com/ap1000_glance.html

WCI, 2012. Coal Statistics. World Coal Institute. Available at: http://www.worldcoal.org/resources/coal-statistics/

Wildbolz, C. (2007). *Life cycle assessment of selected technologies for CO2 transport and sequestration*. Diploma Dissertation, Swiss Federal School of Technology (ETH), Zurich.

WNA (2010). *Generation IV Nuclear Reactors.* World Nuclear Association. December, 2010. Available at: http://www.world-nuclear.org/info/inf77.html

WNA (2012a). *Advanced Nuclear Power Reactors.* World Nuclear Association. April, 2012. Available at: http://www.world-nuclear.org/info/inf08.html

WNA (2012b). *Fast Neutron Reactors.* World Nuclear Association. May, 2012. Available at: http://www.world-nuclear.org/info/inf23.html

WNA (2012c). *World Uranium Mining.* World Nuclear Association. May, 2012. Available at: http://www.world-nuclear.org/info/inf23.html

WNA (2012d). *The Economics of Nuclear Power.* World Nuclear Association. July, 2012. Available at: http://world-nuclear.org/info/inf02.html

WNA (2012e). *Nuclear Power in France.* World Nuclear Association. December, 2012. Available at: http://www.world-nuclear.org/info/inf40.html

WNA (2013a). *Nuclear Development in the United Kingdom.* World Nuclear Association. January, 2013. Available at: http://world-nuclear.org/info/Country-Profiles/Countries-T-Z/Appendices/Nuclear-Development-in-the-United-Kingdom/#.UaZ6F0DWRqU

WNA (2013b). *Nuclear Power in the United Kingdom.* World Nuclear Association. April, 2013. Available at: http://www.world-nuclear.org/info/Country-Profiles/Countries-T-Z/United-Kingdom/#.UabqbEDWRqW

WNA (2013c). *Plans for New Reactors Worldwide.* World Nuclear Association. March, 2013. Available at: http://world-nuclear.org/info/Current-and-Future-Generation/Plans-For-New-Reactors-Worldwide/#.Uabrr0DWRqU

WNN (2007). Dates revised again for Olkiluoto 3. Friday, August 10th, 2007. Available at: http://www.world-nuclear-news.org/newsarticle.aspx?id=13848

WNN (2010 May). *Coalition's emerging nuclear policy*. World Nuclear News, May 12 2010, available at: http://www.world-nuclear-news.org/NP_UK_coalition_1205101.html

WNN (2012, June). *Preferred bidder for Hinkley Point contract.* World Nuclear News, June 19 2012, available at: http://www.world-nuclear-news.org/NN-Preferred_bidder_for_Hinkley_Point_contract-1906124.html

World Commission on Environment and Development, 1987. *Our Common Future, The Report of the World Commission on Environment and Development.* Oxford University Press, Oxford.

Yang, H., Xu, Z. et al. (2008). *Progress in carbon dioxide separation and capture: A review.* Journal of Environmental Sciences **20**(1): 14-27.

11 Appendix 1 SPRIng Briefing Document

Sustainability Assessment of Nuclear Power: An Integrated Approach (SPRIng)

A consortium research project funded by EPSRC and ESRC
Lead institution: The University of Manchester
Academic partners: City University and the University of Southampton

SPRIng Summary

Making decisions about future, more sustainable, energy options is not a trivial task as there are numerous factors to consider. These include technology availability, economic costs, environmental impacts, social acceptability and governance issues. They are often diametrically opposed and, if considered in isolation of each other, can lead to unsustainable decisions. Therefore, the main challenge here is to address these issues in an integrated, balanced and transparent way.

The SPRIng project aims to contribute towards addressing this challenge by developing an integrated decision-support framework within which these criteria can be explored by different stakeholders, including policy makers, industry and citizens. This framework will allow nuclear power to be compared to other electricity-generating options. In addition to this, sustainability assessments of an integrated UK energy mix will be carried out within future energy scenarios.

The framework is being developed in the context of the ongoing debate over the future role of nuclear energy in the UK: a topic that often provokes extreme viewpoints. It will enable the stakeholders to express their views as well as to better understand the viewpoints of others. This will allow them to compare different energy options and identify a more sustainable energy future for the UK by making trade-offs between different sustainability criteria.

The decision-modelling methodology will follow a life-cycle approach to assess and compare different energy options within an integrated UK energy mix. Three of the project’s work packages focus on assessments of the environmental, economic, social and governance issues associated with nuclear and other energy technologies. A fourth work package is developing the decision-support framework and the fifth work package concentrates on eliciting stakeholder feedback and communicating the results.

Project duration and progress

This three-year project started on 1 March 2008 so that the conclusion of the project is scheduled for March 2011. However, there is a possibility of extending the project for further six months, thus extending its duration to September 2011.

The first year of the project concentrated on extensive literature reviews and identifying gaps in current knowledge.

Work in the second year has focussed on developing the environmental, economic, social and technical indicators via which the sustainability of the energy mix will be assessed. The scenarios that provide the background to the sustainability assessments have also been defined during this period. In addition, the environmental and economic assessments are well underway, as is the decision modelling.

Current work and stakeholder contact

The work is now moving towards eliciting stakeholder preferences and gaining feedback on what has been done thus far (primarily the proposed sustainability indicators). It is to this end that we wish to engage with as wide a group of stakeholders as possible to ensure that all views are fairly accounted for and that all aspects of sustainability have been considered.

By engaging with the SPRIng project your organisation can be at the forefront of informing energy policy and decision-making. It is imperative that all issues are explored thoroughly; in order to achieve this, the researchers need your assistance and expertise.

For more information contact christine.a.greenhalgh@manchester.ac.uk, 0161 306 8854
Dr C. Greenhalgh, School of Chemical Engineering and Analytical Science, The University of Manchester, PO Box 88, Sackville Street, Manchester M60 1QD www.springsustainability.org

12 Appendix 2 SPRIng Expert Stakeholder Questionnaire 1

SPRIng Expert Questionnaire

The overall aim of the SPRIng project is to develop a decision-support framework to enable sustainability assessment of nuclear power in an integrated UK energy mix, relative to other energy options (renewables and fossil-fuel). Sustainability assessment will be on a life cycle basis (from 'cradle to grave') and will involve consideration of technical, economic, environmental and social criteria. For these purposes, we have developed a set of sustainability indicators which are presented in the next section.

We would like to seek your views on which sustainability indicators you believe should be considered in assessing the sustainability of nuclear and other energy options and how important they are to you and your organisation.

By answering this questionnaire as comprehensively as possible you will have direct input into how we develop a framework for assessing the sustainability of nuclear and other energy options in the UK.

Name of Respondent:

Company/Organisation Represented:

Date of Completion:

1. Please indicate the relative importance of each of the technical indicators below.

	Impact Category	Potential Indicator(s)	Make Your Rating			
			1	2	3	4
Technical	**Operability**	Capacity factor				
		Availability factor				
		Dispatchability (ability to respond to peak)				
	Technological Lock-in	Plant operational life				
		Flexibility (ability to adapt to changing energy requirements)				
	Immediacy	Time to plant start-up				
	Fuel Use	Fuel use				

2. Please indicate the relative importance of each of the economic indicators below.

	Impact Category	Potential Indicator(s)	Make Your Rating			
			1	2	3	4
Economic	**Levelised Cost of Generation**	Capital costs				
		Operation and maintenance costs				
		Fuel costs				
		Decommissioning costs				
		Total production costs				
	Cost Variability	Fuel price sensitivity				
	Local Economic Impacts	Proportion of spending on local suppliers				
		Proportion of management hired from local community				
		Direct payments to local community				
	Environmental Costs	Expenditure on environmental protection				
	Health and Safety Costs	Expenditure on H&S training				
		Fines for breaches of H&S legislation				
	Detriment to Investment in Other Energy Options	Financial assistance from government				
	National/International Impacts	Contribution to GDP				

3. Please indicate the relative importance of each of the environmental indicators below.

	Impact Category	Potential Indicator(s)	Make Your Rating			
			1	2	3	4
Environmental	**Depletion of Abiotic Resources**	Recyclability of input materials/fuels				
		Use of fossil fuel derived energy				
		Lifetime of global fuel reserves at current extraction rates				
		Use of other abiotic resources				
	Water Use	Total water use				
		Percentage of water reused/recycled				
		Water bodies significantly affected				
	Global Warming Potential	GHG emissions				
	Ozone Depletion Potential	CFC and halogenated HC emissions				
	Acidification Potential	SO_2, NO_x, HCl and NH_3 emissions				
	Eutrophication Potential	N, NO_x, NH_4^+, PO_4^{3-} etc.				
	Photochemical Smog Potential	VOCs and NO_x				
	Eco-toxicity Potential	Freshwater				
		Marine				
		Terrestrial				
	Land Use	Land use				
		Land reuse				
	Waste	Non-radioactive hazardous waste production				
		Radioactive waste production: HLW				

4. Please indicate the relative importance of each of the social indicators below.

	Impact Category	Potential Indicator(s)	Make Your Rating			
			1	2	3	4
Social	**Human Health Impacts**	Worker fatalities, excluding large accidents (including contractors/sub-contractors)				
		Human toxicity potential				
		Human health impacts from radiation				
		Average direct radiation dose to workers				
	Accident Risk	Fatalities due to large accidents				
	Employment	Direct employment				
		Total employment (indirect+direct)				
	Local Impacts	Involvement in community projects				
		Infrastructure improvements resulting from operations				
		Percentage of sites with 'fly in, fly out' operations				
	Intergenerational Equity	Problems created with no current solution				
		Active waste management required for future generations				
	Corruption	Improper business dealings				
	Human Rights	Number of indigenous peoples' rights violations				
		Child labour				
	Nuclear Proliferation	Mass of Pu transported				
		Mass of Pu stored				
	Energy Security	Amount of imported oil/coal/gas avoided				
		Security of fuel supply				

5. Please provide any feedback and comments for each of the indicator sets (given in questions 1-4) and suggest any additional indicators that you think may have been missed.

Indicator Set	**General Feedback/Comments**	**Additional Suggested Indicators**
Environmental		
Economic		
Social		
Technical		

6. Does your company/organisation collect or hold any data/information which would be useful in evaluating the indicators listed in questions 1-4? If so, please provide the details.

7. Does your company/organisation collect or hold any data/information which would be useful in evaluating the indicators you may have suggested as part of question 5? If so, please provide the details.

8. With respect to the decision-support framework and sustainability assessment of different energy options, what would kind of question would you like to be able to ask? What should we include in the decision-support framework?

13 Appendix 3 Expert Multi-Criteria Perspectives Survey

This survey is being carried out by a PhD research student as part of the SPRIng project, whose aim is to identify the main sustainability issues and impacts associated with electricity generation in the UK. For more information on the SPRIng project, please visit:
http://www.springsustainability.org/

The SPRIng project is being carried out by The University of Manchester in collaboration with City University and The University of Southampton.

The overall aim of the PhD project is to develop a methodology for evaluating the sustainability of electricity generation in the UK. The evaluation will take into account environmental, economic and social impacts of electricity generation from different fuels, including fossil, nuclear and renewable. As part of the methodology development, the project seeks to identify what experts think are the main issues and impacts, both positive and negative, of electricity generation in the UK. This information will then inform how we assess the sustainability impacts of electricity generation.

By engaging with the SPRIng project your organisation can be at the forefront of informing energy policy and decision-making. It is imperative that all issues are explored thoroughly; in order to achieve this, the researchers need your assistance and expertise.

We would therefore like to seek your views on the issues listed below, and also to ask you to suggest issues important to you which may not be mentioned in this survey.

All answers will be annonymised and used for research purposes only.

HOW TO COMPLETE THIS SURVEY

The survey consists of 11 questions and should take no longer than 30 minutes to complete.

Please read each question carefully and tick a relevant box to indicate your answer.

If you do not understand or cannot answer the question, please tick the box labelled ‘Don’t know’.

If you acknowledge the above statements and give your consent to participate in this research, please tick the box below.

☐ I consent to my data being used in this survey upon submission of this questionnaire. All data will be anonymised.

YOUR OPINION ON DIFFERENT SOURCES OF ELECTRICITY

Q1 How favourable or unfavourable is your overall opinion of the following energy sources and fuels currently used for generating electricity in the UK?

PLEASE EXPRESS YOUR OPINION FOR EACH ENERGY SOURCE LISTED BELOW.

Electricity source/fuel	Very favourable	Mainly favourable	Neither favourable nor unfavourable	Mainly unfavourable	Very unfavourable	No opinion	Don't know
Biomass-fired power (includes: wood, energy crops, municipal waste)							
Coal-fired power							
Gas-fired power							
Hydroelectric power							
Nuclear power							
Oil-fired power							
Sun/solar power							
Wind power							

MULTICRITERIA PERSPECTIVES ON DIFFERENT SOURCES OF ELECTRICITY

The problem faced by the stakeholders who wish to evaluate impacts of electricity-generating options to inform policy decisions is that there is no option that is superior for all sustainability (economic, environmental and social) aspects. This means that a ‘sustainable’ solution can only be identified by trading-off different sustainability aspects. This typically requires stakeholder elicitation of preferences for sustainability criteria considered.

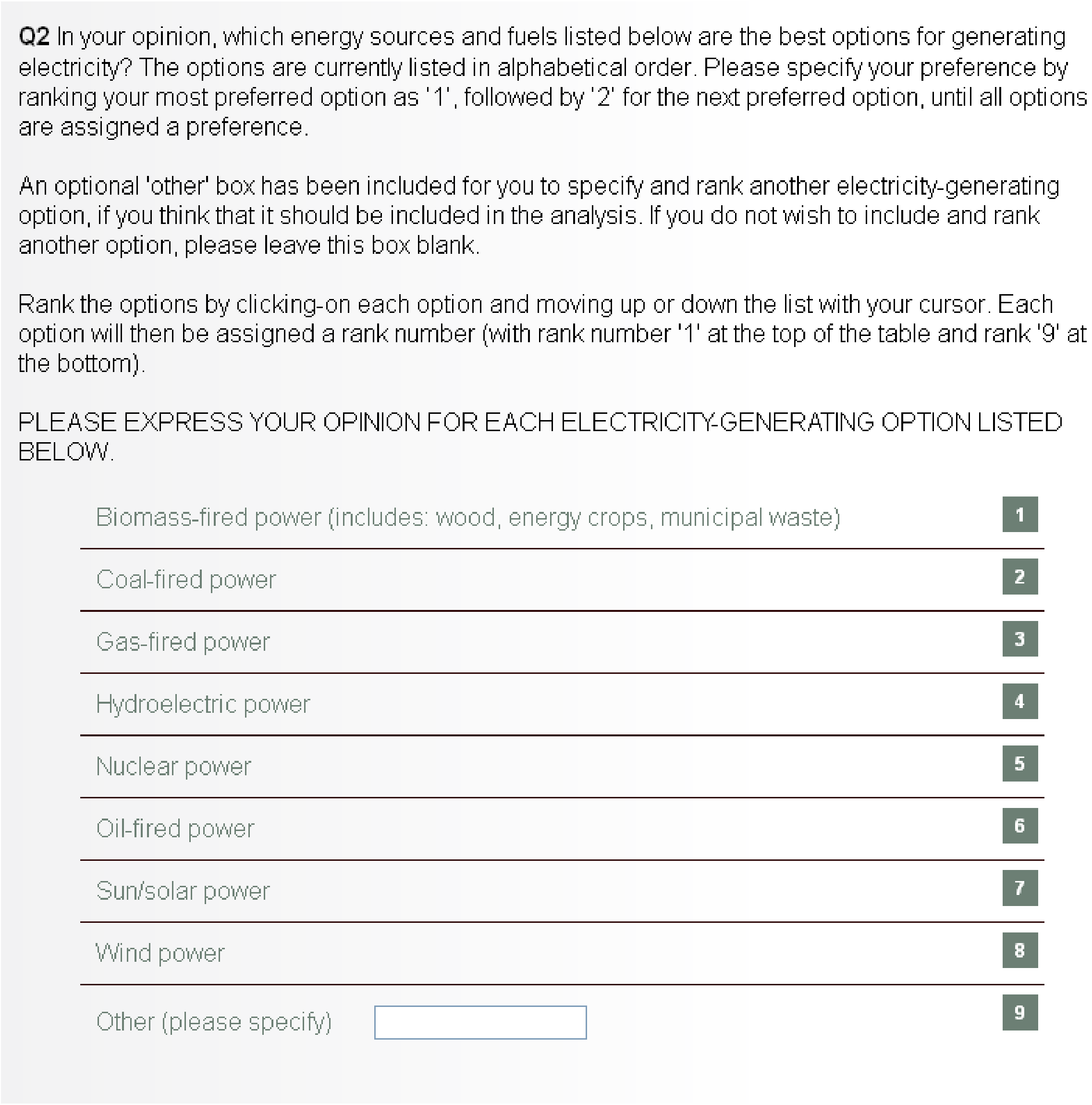
Multi-Criteria Decision-Analysis (MCDA) can be used for these purposes. MCDA tools provide a way to handle conflict between competing decision criteria in a systematic, structured and transparent way. In addition, MCDA can help in resolving disagreement if stakeholders have different views on the relative importance of the considered criteria.

It is important to stress that MCDA is not a tool for providing the ‘right’ solution in a decision problem. Instead, it is an aid that helps decision-makers and stakeholders to organise the information, think of the consequences and explore their own preferences.

In this research, we are using MCDA as a decision-support tool; therefore, the next set of questions is related to the questions normally asked in MCDA. The questions aim to elicit:

- your preferences for electricity-generating technologies for the UK; and
- your preferences for the sustainability criteria (or indicators) that you believe are most important to consider when evaluating the sustainability of electricity-generating technologies.

Your feedback will then help to identify how sustainable different electricity-generating options may be for different stakeholders.



Q2 In your opinion, which energy sources and fuels listed below are the best options for generating electricity? The options are currently listed in alphabetical order. Please specify your preference by ranking your most preferred option as '1', followed by '2' for the next preferred option, until all options are assigned a preference.

An optional 'other' box has been included for you to specify and rank another electricity-generating option, if you think that it should be included in the analysis. If you do not wish to include and rank another option, please leave this box blank.

Rank the options by clicking-on each option and moving up or down the list with your cursor. Each option will then be assigned a rank number (with rank number '1' at the top of the table and rank '9' at the bottom).

PLEASE EXPRESS YOUR OPINION FOR EACH ELECTRICITY-GENERATING OPTION LISTED BELOW.

Biomass-fired power (includes: wood, energy crops, municipal waste)	1
Coal-fired power	2
Gas-fired power	3
Hydroelectric power	4
Nuclear power	5
Oil-fired power	6
Sun/solar power	7
Wind power	8
Other (please specify) ☐	9

MULTICRITERIA PERSPECTIVES ON THE SPRING SUSTAINABILITY INDICATORS

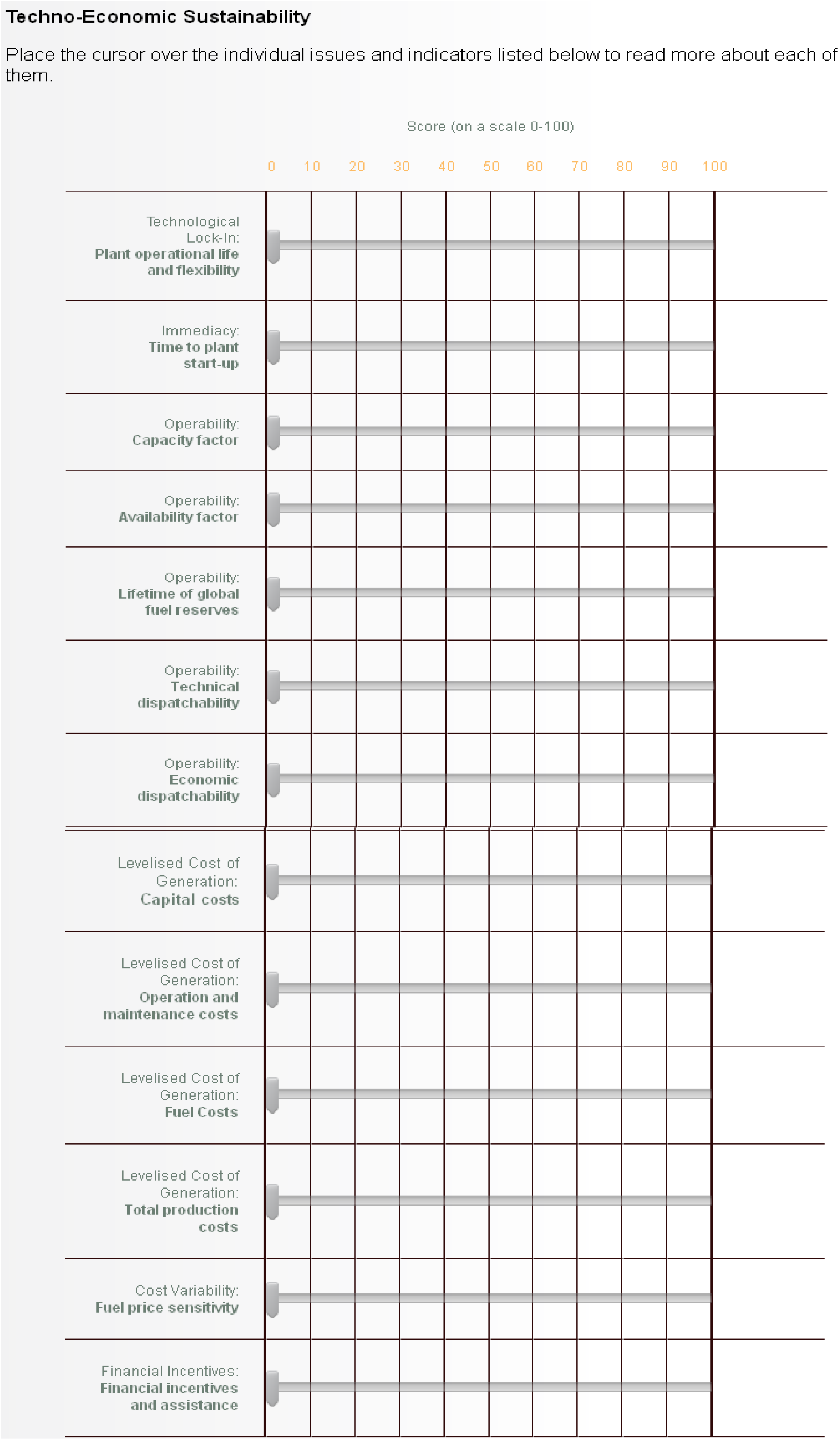
The sustainability indicators listed below have been identified in a previous consultation of experts as important to consider when comparing and assessing the sustainability of different electricity-generating technologies for the UK. The indicators are listed under the following categories: techno-economic; environmental and social. Please specify the relative importance you would place on each of the indicators in assessing the sustainability of different electricity-generation options for the UK.

Q3 In your opinion, which techno-economic indicators are the most important in assessing and comparing the sustainability of electricity-generating options?

Please indicate your preferences by following these instructions:

- assume a hypothetical scale of 0-100, with a value of 100 representing the most important and 0 representing the least important indicator;
- assign the **most important** indicator a score of **100** (do this by moving the score bar to 100 next to the chosen indicator);
- then assign each subsequent indicator to a position on the scale that you think represents its relative importance in relation to all the other indicators (this could be any number between 100 and 0);
- assign indicators that you consider equally important the same value;
- make sure that you assign the **least important** indicator a score of **0** (you will need to click on the score bar of the indicator(s) that you wish to assign a score of 0 for the score to be recorded).

PLEASE EXPRESS YOUR OPINION FOR EACH INDICATOR LISTED BELOW.



Techno-Economic Sustainability

Place the cursor over the individual issues and indicators listed below to read more about each of them.

Technological Lock-In: **Plant operational life and flexibility**

Immediacy: **Time to plant start-up**

Operability: **Capacity factor**

Operability: **Availability factor**

Operability: **Lifetime of global fuel reserves**

Operability: **Technical dispatchability**

Operability: **Economic dispatchability**

Levelised Cost of Generation: **Capital costs**

Levelised Cost of Generation: **Operation and maintenance costs**

Levelised Cost of Generation: **Fuel Costs**

Levelised Cost of Generation: **Total production costs**

Cost Variability: **Fuel price sensitivity**

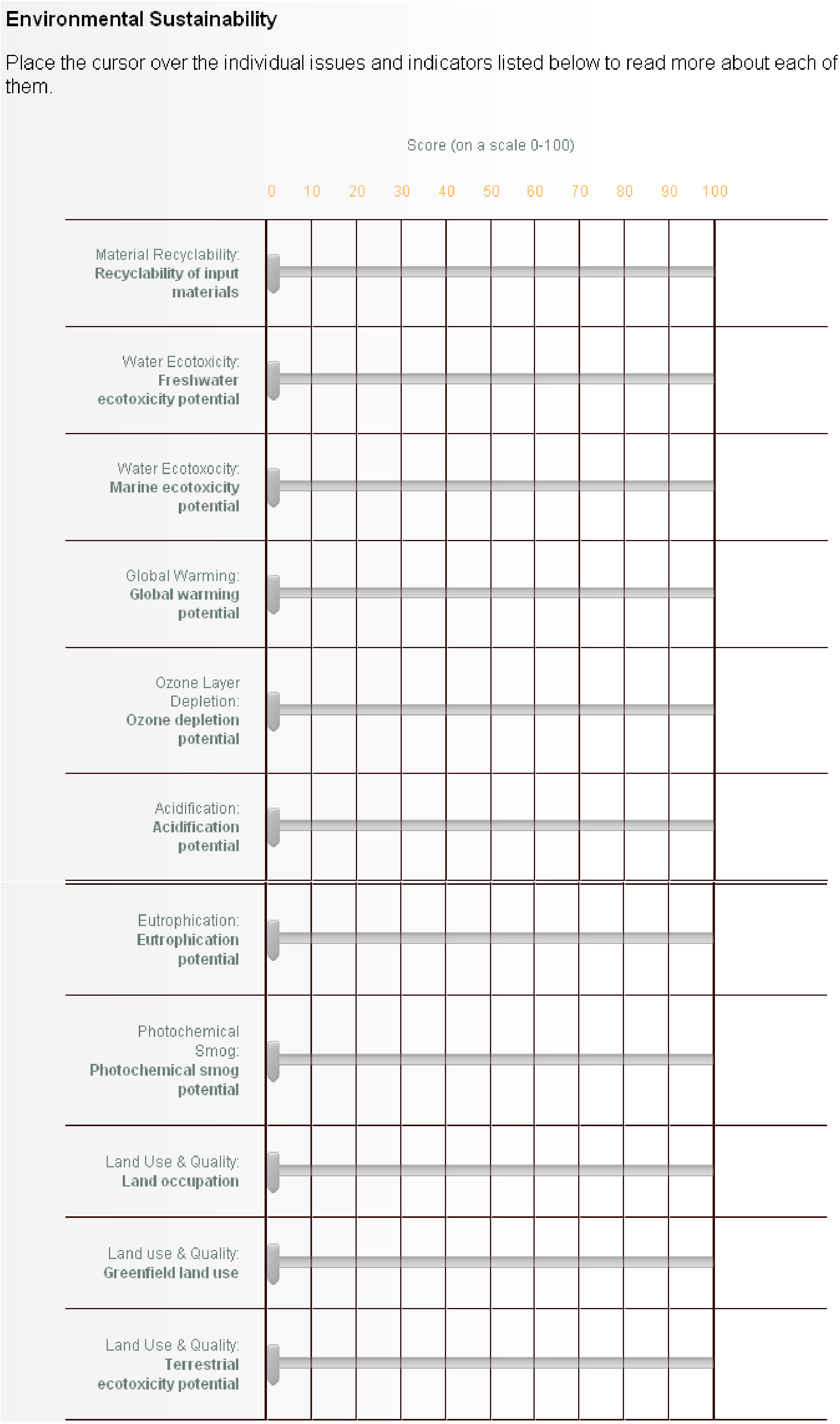
Financial Incentives: **Financial incentives and assistance**

Q4 In your opinion, which environmental indicators are the most important in assessing and comparing the sustainability of electricity-generating options?

Please indicate your preferences by following these instructions:

- assume a hypothetical scale of 0-100, with a value of 100 representing the most important and 0 representing the least important indicator;
- assign the **most important** indicator a score of **100** (do this by moving the score bar to 100 next to the chosen indicator);
- then assign each subsequent indicator to a position on the scale that you think represents its relative importance in relation to all the other indicators (this could be any number between 100 and 0);
- assign indicators that you consider equally important the same value;
- make sure that you assign the **least important** indicator a score of **0** (you will need to click on the score bar of the indicator(s) that you wish to assign a score of 0 for the score to be recorded).

PLEASE EXPRESS YOUR OPINION FOR EACH INDICATOR LISTED BELOW.



Environmental Sustainability

Place the cursor over the individual issues and indicators listed below to read more about each of them.

Score (on a scale 0-100)

Material Recyclability: **Recyclability of input materials**

Water Ecotoxicity: **Freshwater ecotoxicity potential**

Water Ecotoxocity: **Marine ecotoxicity potential**

Global Warming: **Global warming potential**

Ozone Layer Depletion: **Ozone depletion potential**

Acidification: **Acidification potential**

Eutrophication: **Eutrophication potential**

Photochemical Smog: **Photochemical smog potential**

Land Use & Quality: **Land occupation**

Land use & Quality: **Greenfield land use**

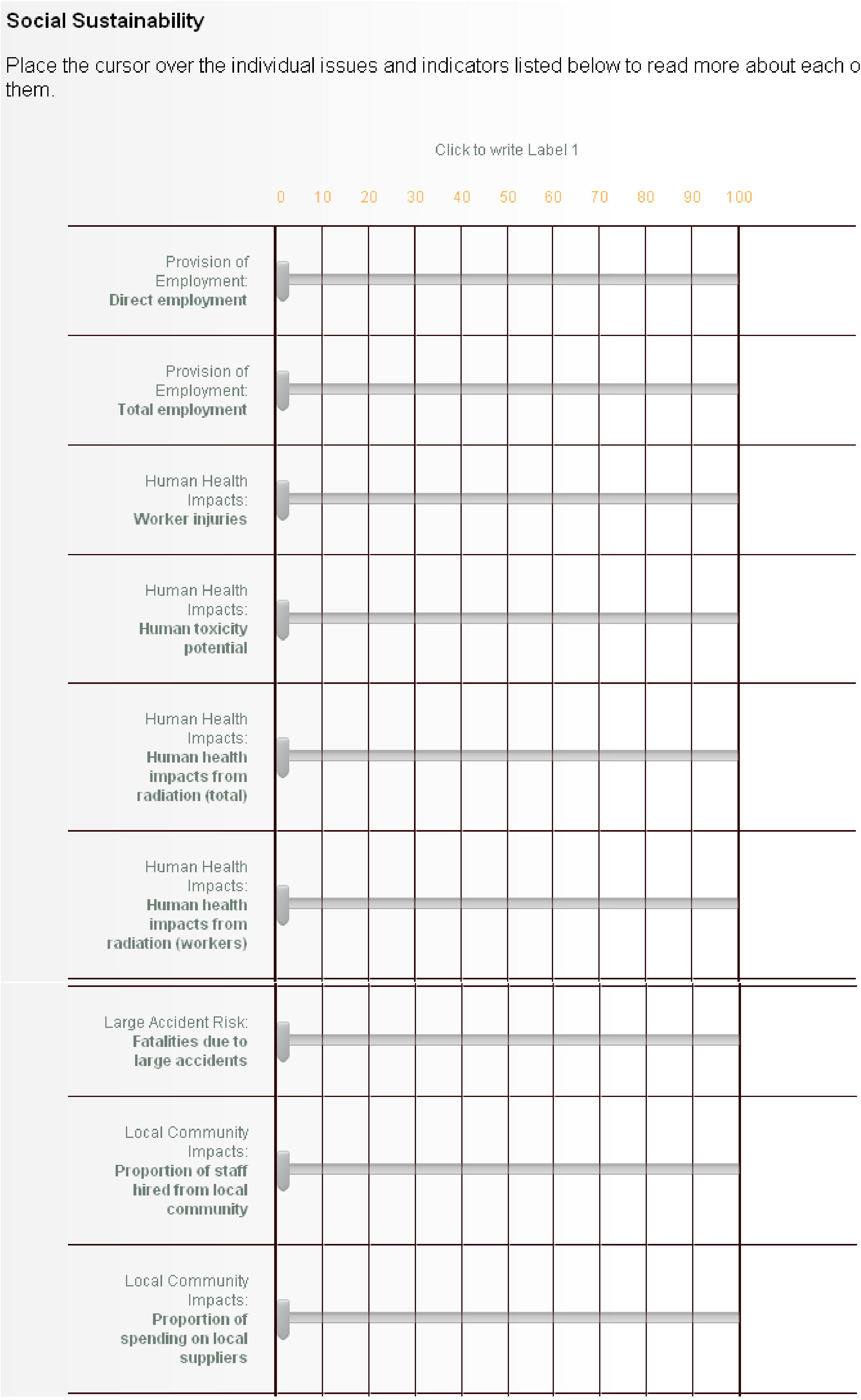
Land Use & Quality: **Terrestrial ecotoxicity potential**

Q5 In your opinion, which social indicators are the most important in assessing and comparing the sustainability of electricity-generating options?

Please indicate your preferences by following these instructions:

- assume a hypothetical scale of 0-100, with a value of 100 representing the most important and 0 representing the least important indicator;
- assign the **most important** indicator a score of **100** (do this by moving the score bar to 100 next to the chosen indicator);
- then assign each subsequent indicator to a position on the scale that you think represents its relative importance in relation to all the other indicators (this could be any number between 100 and 0);
- assign indicators that you consider equally important the same value;
- make sure that you assign the **least important** indicator a score of **0** (you will need to click on the score bar of the indicator(s) that you wish to assign a score of 0 for the score to be recorded).

PLEASE EXPRESS YOUR OPINION FOR EACH INDICATOR LISTED BELOW.



Social Sustainability

Place the cursor over the individual issues and indicators listed below to read more about each of them.

Provision of Employment: **Direct employment**

Provision of Employment: **Total employment**

Human Health Impacts: **Worker injuries**

Human Health Impacts: **Human toxicity potential**

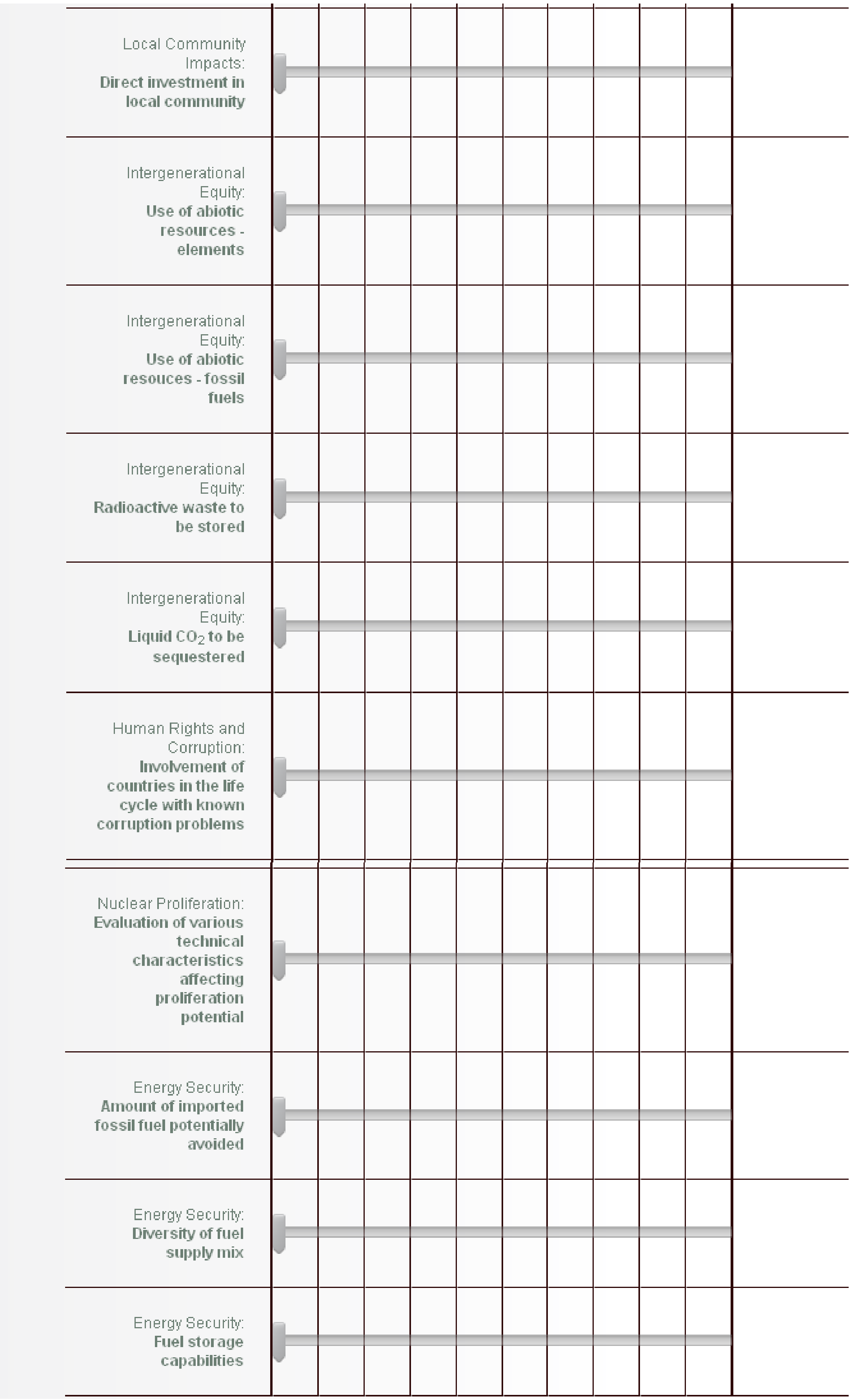
Human Health Impacts: **Human health impacts from radiation (total)**

Human Health Impacts: **Human health impacts from radiation (workers)**

Large Accident Risk: **Fatalities due to large accidents**

Local Community Impacts: **Proportion of staff hired from local community**

Local Community Impacts: **Proportion of spending on local suppliers**



Local Community Impacts: **Direct investment in local community**

Intergenerational Equity: **Use of abiotic resources - elements**

Intergenerational Equity: **Use of abiotic resouces - fossil fuels**

Intergenerational Equity: **Radioactive waste to be stored**

Intergenerational Equity: **Liquid CO_2 to be sequestered**

Human Rights and Corruption: **Involvement of countries in the life cycle with known corruption problems**

Nuclear Proliferation: **Evaluation of various technical characteristics affecting proliferation potential**

Energy Security: **Amount of imported fossil fuel potentially avoided**

Energy Security: **Diversity of fuel supply mix**

Energy Security: **Fuel storage capabilities**

MULTICRITERIA PERSPECTIVES ON DIFFERENT SUSTAINABILITY ASPECTS

Q6 In your opinion, which aspect (or pillar) of sustainability is the most important in the sustainability assessment of electricity-generating options?

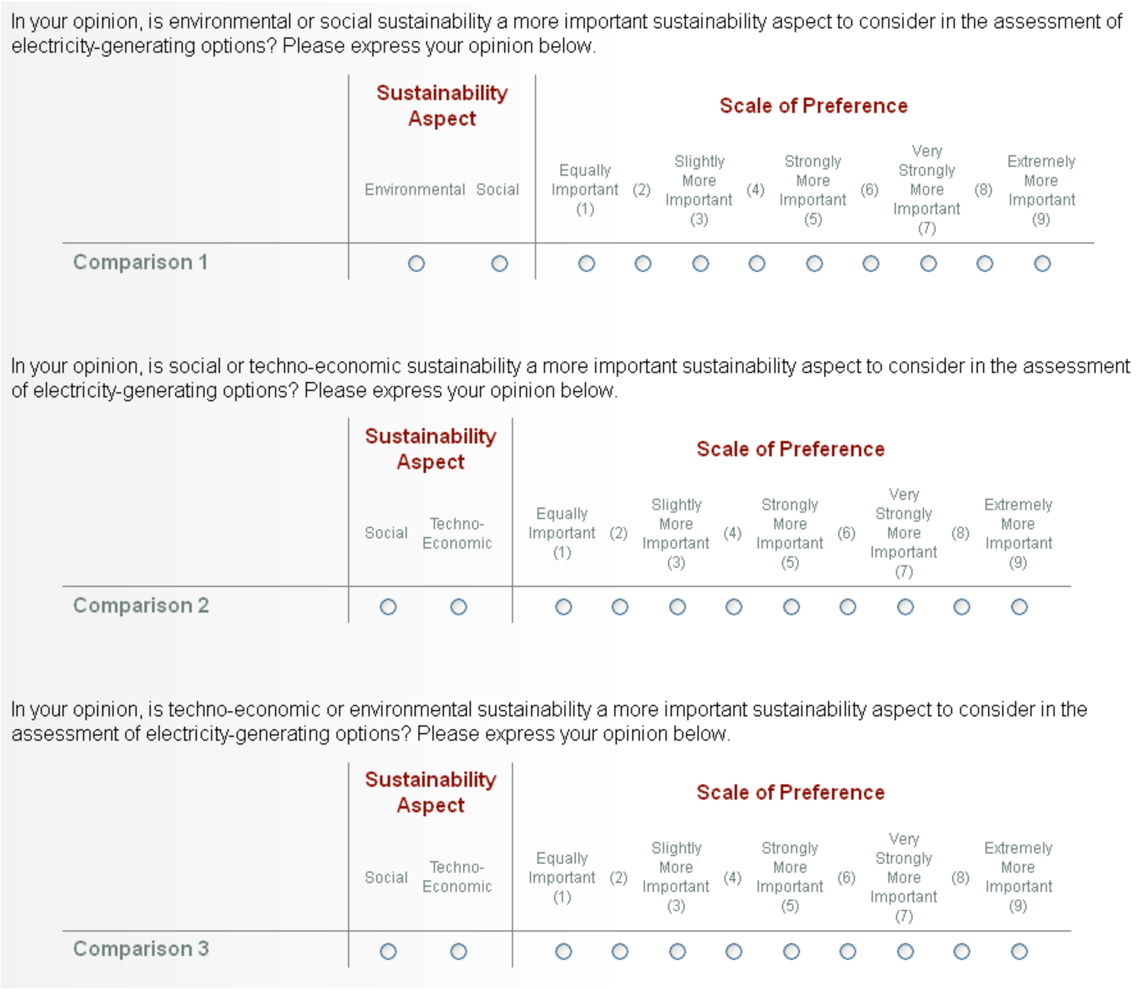
Please indicate your preferences by following these instructions:

- assume a scale of 1-9;
- consider two sustainability aspects at a time as shown in the tables below;
- indicate which sustainability aspect you consider to be more important in the first column; and
- assign an appropriate value between 1 and 9 (the scale is detailed below) to indicate how much more you prefer one sustainability aspect over the other.

1 = equally important
3 = slightly more important
5 = strongly more important
7 = very strongly more important
9 = extremely more important

Intermediate values of 2, 4, 6 and 8 may also be used.

PLEASE EXPRESS YOUR OPINION FOR EACH PAIR OF SUSTAINABILITY ASPECTS LISTED BELOW.



In your opinion, is environmental or social sustainability a more important sustainability aspect to consider in the assessment of electricity-generating options? Please express your opinion below.

	Sustainability Aspect		Scale of Preference								
	Environmental	Social	Equally Important (1)	(2)	Slightly More Important (3)	(4)	Strongly More Important (5)	(6)	Very Strongly More Important (7)	(8)	Extremely More Important (9)
Comparison 1	○	○	○	○	○	○	○	○	○	○	○

In your opinion, is social or techno-economic sustainability a more important sustainability aspect to consider in the assessment of electricity-generating options? Please express your opinion below.

	Sustainability Aspect		Scale of Preference								
	Social	Techno-Economic	Equally Important (1)	(2)	Slightly More Important (3)	(4)	Strongly More Important (5)	(6)	Very Strongly More Important (7)	(8)	Extremely More Important (9)
Comparison 2	○	○	○	○	○	○	○	○	○	○	○

In your opinion, is techno-economic or environmental sustainability a more important sustainability aspect to consider in the assessment of electricity-generating options? Please express your opinion below.

	Sustainability Aspect		Scale of Preference								
	Social	Techno-Economic	Equally Important (1)	(2)	Slightly More Important (3)	(4)	Strongly More Important (5)	(6)	Very Strongly More Important (7)	(8)	Extremely More Important (9)
Comparison 3	○	○	○	○	○	○	○	○	○	○	○

YOUR OPINION ON THE IMPACTS OF ELECTRICITY GENERATION

Q7 Are there any additional issues that you believe are important to consider when assessing and comparing the sustainability of different electricity-generating options?

If so, please specify the issue(s) below.

Q8 Please indicate why you think the issue(s) that you specified in the previous question is(are) important to consider.

Q9 Do you have any other feedback / comments / information regarding the methods used in this research project or regarding any other aspect(s) of the SPRIng project?

If so, please specify below.

YOUR WORK DETAILS

Q10 Please supply the following information about your work:

Sector represented by your company / organisation:

PLEASE CHOOSE FROM THE FOLLOWING.

Energy Supplier
Non-Governmental Organisation
Government Energy or Environmental Agency
Regulator / Government Authority
Association (e.g. trade or industry)
Politician
Researcher / Academic
Consultant
Other (please specify) ☐

Is the company / organisation that you work for specifically within any of the following industries?

PLEASE CHOOSE FROM ONE OR MORE OF THE FOLLOWING.

Coal industry
Gas industry
Nuclear industry
Oil industry
Renewable energy industry
Environmental pressure group or organisation
None

We may be conducting further research on this subject. Would you be willing to be contacted again in the next 3 to 12 months to complete a follow-up questionnaire?

☐ Yes
☐ No

Title:
☐

Contact name:
☐

Company / Organisation represented:
☐

Position within the company / organisation:
☐

Email address:
☐

Postal address:
☐

ABOUT YOU

The final set of questions asks you about yourself to help us find out if there are any differences between the views of different groups of people.

ALL THE INFORMATION YOU PROVIDE ABOUT YOURSELF WILL BE KEPT STRICTLY CONFIDENTIAL.

Q11 Please supply the following information about yourself.
Which of these age groups are you in?

☐ 16-24
☐ 25-34
☐ 35-44
☐ 45-54
☐ 55-59
☐ 60-64
☐ 65-74
☐ 75+

Are you....

☐ Male
☐ Female

Which of these groups do you belong to?

☐ White British
☐ White Irish
☐ Other White background
☐ Black or Black British Caribbean
☐ Black or Black British African
☐ Any other Black background
☐ Mixed White and Black Caribbean
☐ Mixed White and Black African
☐ Mixed White and Asian
☐ Any other mixed background
☐ Asian or Asian British Indian
☐ Asian or Asian British Pakistani
☐ Asian or Asian British Bangladeshi
☐ Chinese
☐ Other ethnic group

Please specify which of the following is the highest educational or professional qualification you have obtained (if still studying, select the highest qualification received so far).

- ☐ GCSE/O-level/CSE
- ☐ Vocational qualification (NVQ1+2)
- ☐ A level or equivalent (=NVQ3)
- ☐ Bachelor Degree or equivalent (=NVQ4)
- ☐ Masters
- ☐ PhD
- ☐ Other
- ☐ No formal qualifications
- ☐ Still studying

Thank you very much for taking part in this survey and helping us with our research project.

14 Appendix 4 Description of Sustainability Indicators for Expert Survey 2

Techno-economic indicators

Capital costs

Initial set-up costs of the power plant / electricity-generating installation.

Operation and maintenance costs

Ongoing running costs incurred throughout the operational period of a power plant's / electricity-generating installation's lifetime.

Fuel costs

Total life cycle cost of fossil / nuclear fuels used in electricity-generation.

Total production costs

Total life cycle costs of electricity production.

Fuel price sensitivity

Ratio of the fuel cost to the total production cost.

Financial incentives and assistance

Total contribution to the costs of electricity production from the government or regulatory measures (e.g. Renewables Obligation Certificates).

Capacity factor

The average percentage of maximum capacity at which a power plant operates.

Availability factor

The average percentage of time during which a plant is technically able to produce electricity.

Technical dispatchability

Evaluation of a technology's ability to load-follow based on its relative ranking in four criteria (ramp-up rate, ramp-down rate, minimum up time, minimum down time).

Economic dispatchability

Financial suitability of a technology to load-following expressed as the ratio of capital cost to total levelised production cost.

Lifetime of global fuel reserves

A rough indication of the lifetime of global fuel reserves.

Plant operational life and flexibility

A measure of technological lock-in that penalises long lifetimes and rewards ability to provide trigeneration, net negative carbon emissions and/or thermochemical hydrogen production.

Time to plant start-up

Estimated construction time.

Environmental indicators

Recyclability of input materials

Potential recyclability of power plant components upon decommissioning.

Freshwater eco-toxicity potential

A measure of the life cycle emission of toxic chemicals into freshwater.

Marine eco-toxicity potential

A measure of the life cycle emission of toxic chemicals into the marine environment.

Global warming potential

Life cycle emission of greenhouse gases.

Ozone depletion potential

Life cycle emission of ozone layer depleting gases, such as CFCs.

Acidification potential

Life cycle emission of acid gases, such as SO_2.

Eutrophication potential

Life cycle emission of substances that cause biomass growth and oxygen depletion in aquatic environments (such as phosphates).

Photochemical smog potential

Life cycle emission of gases contributing to photochemical smog, such as VOCs (volatile organic compounds).

Land occupation

Life cycle area occupied as a result of power generation multiplied by the time for which it is occupied.

Greenfield land use

Proportion of new build in the UK to be sited on Greenfield land.

Terrestrial eco-toxicity potential

Life cycle emission of toxic chemicals to land.

Social indicators

Direct employment

Employment created directly by the power plant during construction, operation and decommissioning.

Total employment

Employment created directly by the power plant during construction, operation and decommissioning.

and also including indirect employment up and down the supply chain (mining of fuel etc.).

Worker injuries

Total injuries resulting in lost time throughout the life cycle of energy production.

Human toxicity potential

A measure of the impact of life cycle emission of toxic chemicals on human health.

Human health impacts from radiation (total)

The estimated, detriment to worker and public life expectancy and health resulting from radiation emitted throughout the life cycle.

Human health impacts from radiation (workers)

The estimated detriment to worker life expectancy and health resulting from radiation emitted throughout the life cycle.

Fatalities due to large accidents

Estimated life cycle fatality rate from large accidents (based on historical and probabilistic data).

Proportion of staff hired from local community

This is a company- and site-specific indicator (the impact of this is not attributable to specific electricity-generating technologies).

Proportion of spending on local suppliers

This is a company- and site-specific indicator (the impact of this is not attributable to specific electricity-generating technologies).

Direct investment in local community

This is a company- and site-specific indicator (the impact of this is not attributable to specific electricity-generating technologies).

Use of abiotic resources - elements

Life cycle depletion of mineral resources based on current use rate and reserve size.

Use of abiotic resources – fossil fuels

Life cycle fossil fuel use.

Radioactive waste to be stored

Total radioactive waste production ultimately requiring geological storage.

Liquid CO_2 to be sequestered

Total CO_2 destined for geological storage at pressures indicative of depleted oil/gas fields.

Human rights and corruption

Involvement in the life cycle of countries with known corruption problems: the average score of the countries involved in the life cycle, as evaluated by the Transparency International Corruption Perceptions Index.

Nuclear proliferation

Evaluation of various technical characteristics affecting proliferation potential (use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing, and requirement for enriched uranium).

Amount of imported fossil fuel potentially avoided

The amount of fossil fuel that would have to be burnt to provide equivalent energy from the current UK fossil fuel power plant fleet.

Diversity of fuel supply mix

Evaluation of national supply diversity of different fuels based in the Simpson Diversity Index.

Fuel storage capabilities

Volumetric energy density of the fuel as a reflection of how much energy could be stockpiled in a given space.

15 Appendix 5 AHP Weighting Results of the Sustainability Aspects from the Second Stage Expert Questionnaire

Stakeholder	Techno-Economic Values	Environmental Values	Social Values	Percentage Techno-Economic	Percentage Environmental	Percentage Social
1	56.46	65.91	36.58	35.52	41.47	23.01
2	56.92	24.09	41.16	46.59	19.72	33.69
3	69.00	76.45	58.68	33.80	37.45	28.75
4	36.38	31.64	34.53	35.48	30.85	33.67
5	68.69	75.00	59.37	33.83	36.93	29.24
6	65.08	63.82	62.16	34.06	33.40	32.53
7	68.00	68.09	56.11	35.38	35.43	29.19
8	62.31	60.91	49.47	36.08	35.27	28.65
9	62.69	69.09	56.32	33.33	36.73	29.94
10	73.08	59.09	66.32	36.82	29.77	33.41
11	53.46	52.91	69.32	30.43	30.12	39.45
12	70.77	64.18	77.89	33.25	30.15	36.60
13	61.77	45.00	50.05	39.39	28.69	31.92
14	70.00	30.91	63.16	42.67	18.84	38.50
15	77.08	46.27	25.63	51.74	31.06	17.20
16	42.23	31.82	62.58	30.91	23.29	45.80
17	39.85	51.91	48.26	28.46	37.07	34.47
18	36.38	35.27	32.58	34.91	33.84	31.25
19	57.62	50.45	49.84	36.49	31.95	31.56
20	69.46	76.82	62.89	33.21	36.72	30.07
21	78.08	85.45	73.42	32.95	36.06	30.99
22	42.31	33.64	27.11	41.06	32.64	26.30
23	54.85	49.36	44.42	36.90	33.21	29.89
24	41.54	42.73	47.37	31.56	32.46	35.98
25	40.54	40.27	56.00	29.63	29.44	40.93
26	69.15	62.82	62.37	35.58	32.32	32.09
27	59.23	30.55	57.63	40.18	20.72	39.10
28	63.92	61.64	35.89	39.59	38.18	22.23
29	48.08	37.82	44.74	36.80	28.95	34.25
30	53.31	60.09	67.84	29.41	33.16	37.43
31	64.54	60.27	68.12	33.45	31.24	35.31
32	65.85	80.18	76.00	29.66	36.11	34.23
33	55.69	34.00	35.84	44.36	27.08	28.55
34	70.54	47.82	72.00	37.06	25.12	37.82
35	48.54	85.73	80.53	22.60	39.91	37.49
36	57.54	71.45	50.05	32.14	39.91	27.96
37	84.00	88.09	65.32	35.38	37.11	27.51
38	52.15	71.36	59.58	28.48	38.98	32.54

Stakeholder	Techno-Economic Values	Environmental Values	Social Values	Percentage Techno-Economic	Percentage Environmental	Percentage Social
39	63.92	63.55	65.58	33.11	32.92	33.97
40	62.92	48.00	55.79	37.74	28.79	33.46
41	69.46	63.82	48.26	38.26	35.15	26.58
42	63.92	29.18	42.84	47.02	21.47	31.51
43	40.38	27.91	30.37	40.93	28.29	30.78
44	68.46	68.00	59.21	34.99	34.75	30.26
45	56.23	54.91	49.11	35.09	34.27	30.64

16 Appendix 6 Public Engagement Survey 1

IMPACTS OF ELECTRICITY GENERATION IN THE UK

This survey is being carried out by a PhD research student as part of the SPRIng project, whose aim is to identify the main sustainability issues and impacts associated with electricity generation in the UK. For more information on the SPRIng project, please visit: http://www.springsustainability.org/

The SPRIng project is being carried out by The University of Manchester in collaboration with City University and The University of Southampton.

The overall aim of the PhD project is to develop a methodology for evaluating the sustainability of electricity generation in the UK. The evaluation will take into account environmental, economic and social impacts of electricity generation from different fuels, including fossil, nuclear and renewable. As part of the methodology development, the project seeks to identify what different people think are the main issues and impacts, both positive and negative, of electricity generation in the UK. This information will then inform how we assess the sustainability impacts of electricity generation.

We would therefore like to seek your views on the issues listed below, and also to ask you to suggest issues important to you which may not be mentioned in this survey.

We very much hope that you will take part in this survey. As a thank you for your time, if you click '**Yes**' in **Q17**, we will enter you into a free prize draw with a £50 in Amazon vouchers.

All answers will be annonymised and used for research purposes only.

HOW TO COMPLETE THIS SURVEY

This survey can be completed by anyone aged 16 or over, who is ordinarily resident in the UK.

The survey consists of 20 questions and should take no longer than 15 minutes to complete.

Please read each question carefully and tick a relevant box to indicate your answer.

If you do not understand or cannot answer the question, please tick the box labelled 'Don't know'.

If you acknowledge the above statements and give your consent to participate in the investigation, please tick the box below.

☐ I consent to my data being used in this survey upon submission of this questionnaire.

ELECTRICITY GENERATION IN YOUR COMMUNITY

Q1 Are you aware of how far you live from the following installation(s) **currently generating electricity**? To the best of your knowledge, please specify the distance of the installation(s) from your home.

PLEASE TICK ALL THOSE THAT APPLY.

Electricity-generating installation(s)	0-5 miles	6-10 miles	11-20 miles	21-50 miles	51+ miles	Never heard of it	Don't know	None
Biomass-fired power station (includes: wood, energy crops, municipal waste)								
Coal-fired power station								
Gas-fired power station								
Hydroelectric power station								
Nuclear power station								
Oil-fired power station								
Sun/Solar power generation								
Wind farm								

ELECTRICITY GENERATION IN YOUR COMMUNITY

Q2 Are you aware of **plans to build/install** any of the following electricity-generating installation(s) in your local community or near to the area in which you live? To the best of your knowledge, please specify the distance of the proposed installation(s) from your home.

PLEASE TICK ALL THOSE THAT APPLY.

Electricity-generating installation(s)	0-5 miles	6-10 miles	11-20 miles	21-50 miles	51+ miles	Never heard of it	Don’t know	None
Biomass-fired power station (includes: wood, energy crops, municipal waste)								
Coal-fired power station								
Gas-fired power station								
Hydroelectric power station								
Nuclear power station								
Oil-fired power station								
Sun/Solar power generation								
Wind farm								

YOUR OPINION ON DIFFERENT SOURCES OF ELECTRICITY

Q3 How favourable or unfavourable is your overall opinion of the following energy sources and fuels for generating electricity?

PLEASE EXPRESS YOUR OPINION FOR EACH ENERGY SOURCE LISTED BELOW.

Electricity source/fuel	Very favourable	Mainly favourable	Neither favourable nor unfavourable	Mainly unfavourable	Very unfavourable	Never heard of it	No opinion	Don't know
Biomass-fired power (includes: wood, energy crops, municipal waste)								
Coal-fired power								
Gas-fired power								
Hydroelectric power								
Nuclear power								
Oil-fired power								
Sun/solar power								
Wind power								

YOUR OPINION ON THE UK'S FUTURE ELECTRICITY MIX

Q4 The UK's electricity is currently generated from the energy sources listed below. Their current contribution to the UK's electricity mix is specified below in brackets (%). Please indicate, for each energy source, the relative change in contribution you would like to see for the UK's **future** electricity mix.

PLEASE EXPRESS YOUR OPINION FOR EACH ENERGY SOURCE LISTED BELOW.

Electricity source/fuel	Increase contribution	Keep contribution the same	Decrease contribution	Stop generating from this source	Never heard of it	No opinion	Don’t know
Biomass-fired power (includes: wood, energy crops, municipal waste) (currently 3.8%)							
Coal-fired power (currently 28%)							
Gas-fired power (currently 44.5%)							
Hydroelectric power (currently 1.4%)							
Nuclear power (currently 18.6%)							
Oil-fired power (currently 1.2%)							

Sun/solar power (currently 0.005%)							
Wind power (currently 2.5%)							

YOUR OPINION ON THE IMPACTS OF ELECTRICITY GENERATION

Q5 The sustainability issues listed below (alphabetically) have been identified by experts as the most important issues to consider when comparing and assessing the sustainability of different electricity sources. How important are these issues to you?

PLEASE EXPRESS YOUR OPINION FOR EACH ISSUE LISTED BELOW.
Place the cursor over the individual issues listed below to read more about each issue.

Issue	Very important	Mainly important	Neither important nor unimportant	Mainly unimportant	Very unimportant	Never heard of it	No opinion	Don't know
Acid rain								
Civilian fatalities due to large accidents related to electricity generation								
Cost of electricity								
Greenhouse gas emissions								
Human health impacts from radiation								
Human health impacts from toxic substances (excluding radiation)								
Land contamination from toxic substances								
Ozone layer depletion								
Reliability of electricity generation and ability to								

respond to peak demand								
Remaining world fuel reserves								
UK energy security: avoiding imports of fuels								
UK energy security: diversity of fuel supply and ability to store fuel for future use								
Waste management required by future generations								
Water contamination from toxic substances								
Worker fatalities from work-related accidents								

YOUR OPINION ON THE IMPACTS OF ELECTRICITY GENERATION

Q6 Are there any additional issues that you believe are important to consider when assessing and comparing the sustainability of different electricity-generating options?

If so, please specify the issue(s) below.

YOUR OPINION ON THE IMPACTS OF ELECTRICITY GENERATION

Q7 Please indicate why you think the issue(s) that you specified in the previous question is(are) important to consider.

ABOUT YOU

The final set of questions asks you about yourself to help us find out if there are any differences between the views of different groups of people.

ALL THE INFORMATION YOU PROVIDE ABOUT YOURSELF WILL BE KEPT STRICTLY CONFIDENTIAL.

Q8 Do you or any of your family work in any of the following industries or groups?

PLEASE TICK ALL THOSE THAT APPLY.

☐ Coal industry
☐ Gas industry
☐ Nuclear industry
☐ Oil industry
☐ Renewable energy industry
☐ Environmental pressure group or organisation
☐ None

Q9 Are you involved with any of the following **with regard to influencing UK energy policy**?

PLEASE TICK ALL THOSE THAT APPLY.

☐ Environmental pressure group
☐ Individual action (e.g. contacted radio station/newspaper/Member of Parliament/organised a petition/protest etc.)
☐ International organisation
☐ Local authority
☐ Local pressure group
☐ National government
☐ Political group
☐ Site stakeholder group
☐ Trade union
☐ University
☐ None
☐ Other (please specify)

Q10 Which of these age groups are you in?

☐ 16-24
☐ 25-34
☐ 35-44
☐ 45-54
☐ 55-59
☐ 60-64
☐ 65-74
☐ 75+

Q11 Are you....

☐ Male
☐ Female

Q12 Which of the following best describes what you are doing at the moment?

☐ Employee in full-time job (30 hours plus per week)
☐ Employee in part-time job (under 30 hours per week)
☐ Full-time education at school, college or university
☐ Unemployed and looking for work
☐ Unemployed and not looking for work
☐ Permanently sick/disabled
☐ Fully retired from work
☐ Looking after the home
☐ Other

Q13 Which of these groups do you belong to?

- ☐ White British
- ☐ White Irish
- ☐ Other White background
- ☐ Black or Black British Caribbean
- ☐ Black or Black British African
- ☐ Any other Black background
- ☐ Mixed White and Black Caribbean
- ☐ Mixed White and Black African
- ☐ Mixed White and Asian
- ☐ Any other mixed background
- ☐ Asian or Asian British Indian
- ☐ Asian or Asian British Pakistani
- ☐ Asian or Asian British Bangladeshi
- ☐ Chinese
- ☐ Other ethnic group

Q14 Please specify which of the following is the highest educational or professional qualification you have obtained (if still studying, select the highest qualification received so far).

- ☐ GCSE/O-level/CSE
- ☐ Vocational qualification (NVQ1+2)
- ☐ A level or equivalent (=NVQ3)
- ☐ Bachelor Degree or equivalent (=NVQ4)
- ☐ Masters
- ☐ PhD
- ☐ Other
- ☐ No formal qualifications
- ☐ Still studying
- ☐ Don’t know

Q15 Please specify from the list below, the level of employment of the main income earner of your household.

- ☐ Higher managerial, administrative or professional
- ☐ Intermediate managerial, administrative or professional
- ☐ Supervisory, clerical and junior managerial, administrative or professional
- ☐ Skilled manual worker
- ☐ Semi and unskilled manual worker
- ☐ Casual worker, pensioner or on state welfare

Q16 Please provide the **first half** of your postcode. This information will help us to find out if there are any differences in the opinions in different regions of the UK.

☐

Q17 Would you like to be entered into the free prize draw?

- ☐ Yes
- ☐ No

Q18 Would you like to receive a copy of the report summarising the anonymised findings of this survey?

- ☐ Yes
- ☐ No

Q19 We may be conducting further research on this subject. Would you be willing to be contacted again in the next 3 to 12 months to complete a follow-up questionnaire?

- ☐ Yes
- ☐ No

Q20 IF YOU TICKED ‘YES’ IN **Q17** and/or **Q18** & **Q19** PLEASE COMPLETE THE FOLLOWING:

Title:

Name:

Email address:

Daytime telephone number:

Thank you very much for taking part in this survey and helping us with our research project.

17 Appendix 7 Description of Sustainability Issues for Public Survey 1

Acid rain

Acid rain is caused by acid gases such as sulphur dioxide and nitrogen oxides emitted from combustion of some fuels used for electricity generation. Their precipitation causes acidification of waterways and land and can affect fish, vegetation and human health.

Civilian fatalities due to large accidents

Civilian deaths resulting from large accidents related to electricity generation.

Cost of electricity

Cost of electricity generation related to the price which consumers pay for electricity.

Greenhouse gas emissions

Greenhouse gases include carbon dioxide, methane and nitrous oxide. They can be emitted from different electricity-generating options and contribute to global warming and climate change.

Human health impacts from radiation

Human exposure to radiation can cause various health impacts, including radiation sickness and cancer.

Human health impacts from toxic substances (excluding radiation)

Toxic substances such as heavy metals emitted by some electricity-generating options may affect human health, including respiratory diseases and in some cases cancers.

Land contamination from toxic substances

Toxic substances released to the environment can contaminate land and affect animals and plants.

Ozone layer depletion

Depletion of the ozone layer is caused by CFCs which are used as refrigerants. The ozone layer protects us from the ultraviolet (UV) radiation from the Sun. Increased UV radiation can cause skin cancer.

Reliability of electricity generation and ability to respond to peak demand

Some technologies provide a more stable output of electricity whilst others are less reliable due to the intermittent availability of their source of energy. Technologies with a more stable output can also respond better to peak demand of electricity (for example, in the evening due to cooking, watching television etc.).

Remaining world fuel reserves
This is related to the amount of fossil (coal, gas, oil) and nuclear (uranium) fuels remaining available for electricity generation.

UK energy security: avoiding imports of fuels
Decreasing the reliance on the imports of fossil fuels (coal, gas, oil) and increasing the use of energy sources available within the UK could increase the UK's energy security.

UK energy security: diversity of fuel supply and ability to store fuel for future use
Diversifying fuel imports to make the UK less dependent on any one country could help increase the UK's energy security. This can also be improved by being able to store fuels for future use. Some fuels are more suited for storage (e.g. solid and liquid fuels) while others are less so (e.g. gaseous fuels).

Waste management required by future generations
This refers to the need to manage or store for a very long time toxic or dangerous waste generated by some energy technologies.

Water contamination from toxic substances
Toxic substances released to the environment can contaminate rivers, lakes and oceans and affect aquatic organisms.

Worker fatalities from work-related accidents
This refers to work-related deaths associated with electricity generation.

18 Appendix 8 Public Engagement Survey 2

FURTHER PUBLIC PERSPECTIVES ON ELECTRICITY GENERATION IN THE UK

Thank you for taking part in the first phase of this survey and agreeing to take part in this further questionnaire. To remind you, the survey is being carried out by a PhD research student as part of the SPRIng project, whose aim is to identify the main sustainability issues and impacts associated with electricity generation in the UK. For more information on the SPRIng project, please visit: http://www.springsustainability.org/

The SPRIng project is being carried out by The University of Manchester in collaboration with City University and The University of Southampton.

The overall aim of the PhD project is to develop a methodology for evaluating the sustainability of electricity generation in the UK. The evaluation will take into account environmental, economic and social impacts of electricity generation from different fuels, including fossil, nuclear and renewable. As part of understanding the public opinion on the issues and impacts of electricity generation in the UK, we would like to evaluate how much importance different people place on all of the issues identified (which are presented in this questionnaire) and also gauge a level of public understanding of these issues.

We would therefore like to seek your views on the issues listed below, and also your views on different methods of electricity generation.

We very much hope that you will take part in this survey. As a thank you for your time, if you click ‘**Yes**’ in question **9**, we will enter you into a second free prize draw (in addition to the prize draw for the first survey completion) with a £50 prize in Amazon vouchers.

All answers will be annonymised and used for research purposes only.

HOW TO COMPLETE THIS SURVEY

The survey consists of 9 questions and should take no longer than 20 minutes to complete.

Please read each question carefully and tick a relevant box to indicate your answer.

If you do not understand or cannot answer the question, please tick the box labelled ‘Don’t know’.

If you acknowledge the above statements and give your consent to participate in this research, please tick the box below.

☐ I consent to my data being used in this survey upon submission of this questionnaire. All data will be anonymised.

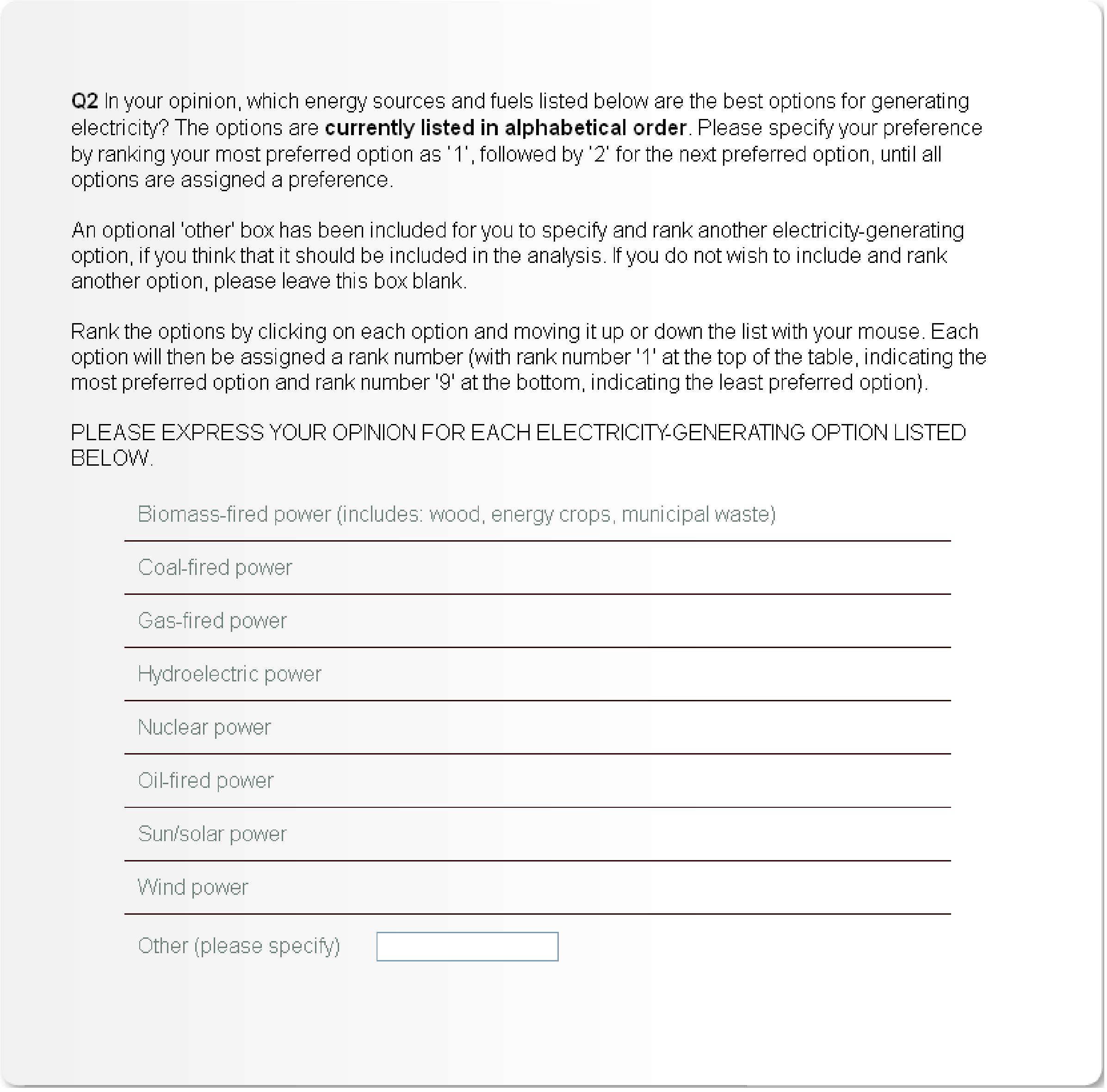
YOUR OPINION ON DIFFERENT SOURCES OF ELECTRICITY

Q1 How favourable or unfavourable is your overall opinion of the following energy sources and fuels currently used for generating electricity in the UK?

PLEASE EXPRESS YOUR OPINION FOR EACH ENERGY SOURCE LISTED BELOW.

Electricity source/fuel	Very favour able	Mainly favour able	Neither favourable nor unfavourable	Mainly unfavou rable	Very unfavou rable	No opinion	Don't know
Biomass-fired power (includes: wood, energy crops, municipal waste)							
Coal-fired power							
Gas-fired power							
Hydroelectric power							
Nuclear power							
Oil-fired power							
Sun/solar power							
Wind power							

YOUR OPINION ON DIFFERENT SOURCES OF ELECTRICITY: RANKING ELECTRICITY-GENERATING OPTIONS



Q2 In your opinion, which energy sources and fuels listed below are the best options for generating electricity? The options are **currently listed in alphabetical order**. Please specify your preference by ranking your most preferred option as '1', followed by '2' for the next preferred option, until all options are assigned a preference.

An optional 'other' box has been included for you to specify and rank another electricity-generating option, if you think that it should be included in the analysis. If you do not wish to include and rank another option, please leave this box blank.

Rank the options by clicking on each option and moving it up or down the list with your mouse. Each option will then be assigned a rank number (with rank number '1' at the top of the table, indicating the most preferred option and rank number '9' at the bottom, indicating the least preferred option).

PLEASE EXPRESS YOUR OPINION FOR EACH ELECTRICITY-GENERATING OPTION LISTED BELOW.

- Biomass-fired power (includes: wood, energy crops, municipal waste)
- Coal-fired power
- Gas-fired power
- Hydroelectric power
- Nuclear power
- Oil-fired power
- Sun/solar power
- Wind power
- Other (please specify) ☐

YOUR OPINION ON NUCLEAR POWER

Q3

i) Has your opinion on nuclear power changed within the past year?

☐ Yes ☐ No

If so, how has your opinion changed and for what reason?

ii) Are you aware of Government plans to build a new generation of eight nuclear power stations in the UK?

☐ Yes ☐ No

iii) The new generation of nuclear power reactors will be built on the site of, or near to the sites of currently operating power plants. If the Government's plans for nuclear power in the UK expand, it is likely that new sites would have to be found for more reactors to be built on.

To what extent to you agree or disagree with the following statements with regard to the Government plans for new nuclear power plants:

PLEASE EXPRESS YOUR OPINION FOR EACH OF THE STATEMENTS BELOW.

I support the current plans for a new generation of nuclear power stations in the UK.

I support the plans in principle, but would want to know more about the advantages and disadvantages of nuclear power before committing my full support.

I would support Government plans for even more nuclear power stations to be built in addition to those already planned.

I would support Government plans for even more nuclear power stations to be built in addition to those already planned, even if that meant that a nuclear power plant might be built within close proximity (under 50 miles) to my home.

I trust the Government to make decisions on energy policy that are beneficial to the economy, society and the environment.

(Range of answer options: strongly agree, tend to agree, neither agree nor disagree, tend to disagree, strongly disagree, no opinion, don't know.)

YOUR OPINION ON ENVIRONMENTAL ISSUES

Q4 To what extent do you agree or disagree with the following statements about climate change and environmental issues?

PLEASE EXPRESS YOUR OPINION FOR EACH OF THE STATEMENTS BELOW.

I think of myself as someone who is concerned about climate change and global warming.

I think of myself of someone who is concerned about wider environmental issues.

I actively try to reduce my carbon footprint.

I actively try to be environmentally friendly.

I take part in campaigning about environmental issues.

I accept biomass-fired power as a viable electricity option to help the UK reduce its carbon emissions.

I accept hydroelectric power as a viable electricity option to help the UK reduce its carbon emissions.

I accept nuclear power as a viable electricity option to help the UK reduce its carbon emissions.

I accept sun/solar power as a viable electricity option to help the UK reduce its carbon emissions.

I accept wind power as a viable electricity option to help the UK reduce its carbon emissions.

(Range of answer options: strongly agree, tend to agree, neither agree nor disagree, tend to disagree, strongly disagree, no opinion, don't know.)

PUBLIC PERSPECTIVES ON THE IMPACTS OF ELECTRICITY GENERATION

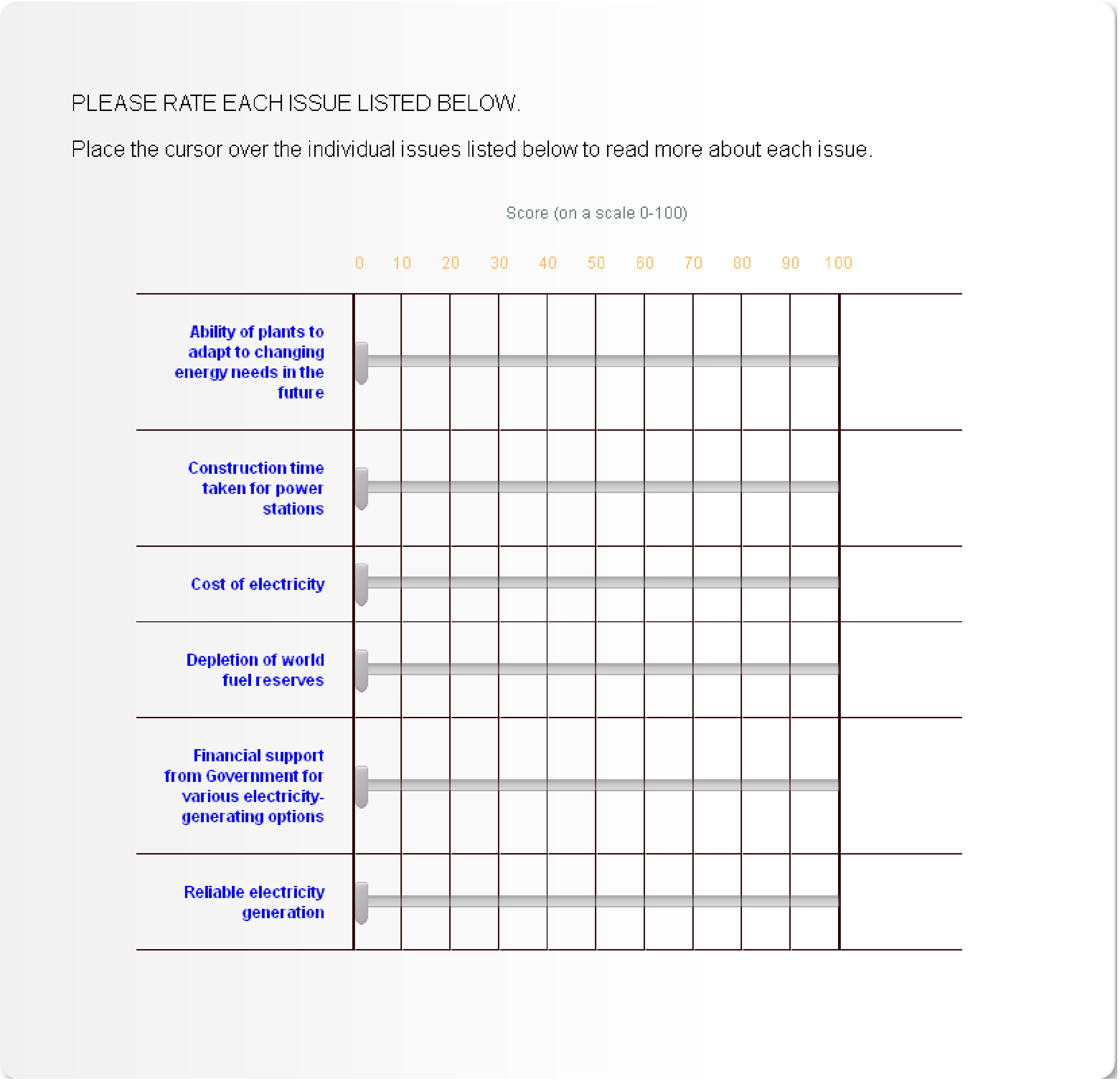
The sustainability issues listed below are separated into technical/economic, environmental and social aspects and are listed alphabetically. These issues (which may have positive or negative impacts) have been identified by experts as the most important issues to consider when comparing and assessing the sustainability of different electricity sources.

Q5 TECHNICAL AND ECONOMIC ISSUES

Consider the technical and economic issues listed below. These issues are associated with the generation and provision of electricity. In your opinion, which technical and economic issues are the most important in evaluating and comparing different electricity-generating options?

Please indicate your preferences by following these instructions:

- assign the **most important** issue a score of **100** (do this by moving the score bar to 100 next to the chosen issue);
- then assign each subsequent issue to a position on the scale that you think represents its relative importance in relation to all the other issues (this could be any number between 100 and 0);
- assign issues that you consider equally important the same value.



PLEASE RATE EACH ISSUE LISTED BELOW.

Place the cursor over the individual issues listed below to read more about each issue.

Ability of plants to adapt to changing energy needs in the future

Construction time taken for power stations

Cost of electricity

Depletion of world fuel reserves

Financial support from Government for various electricity-generating options

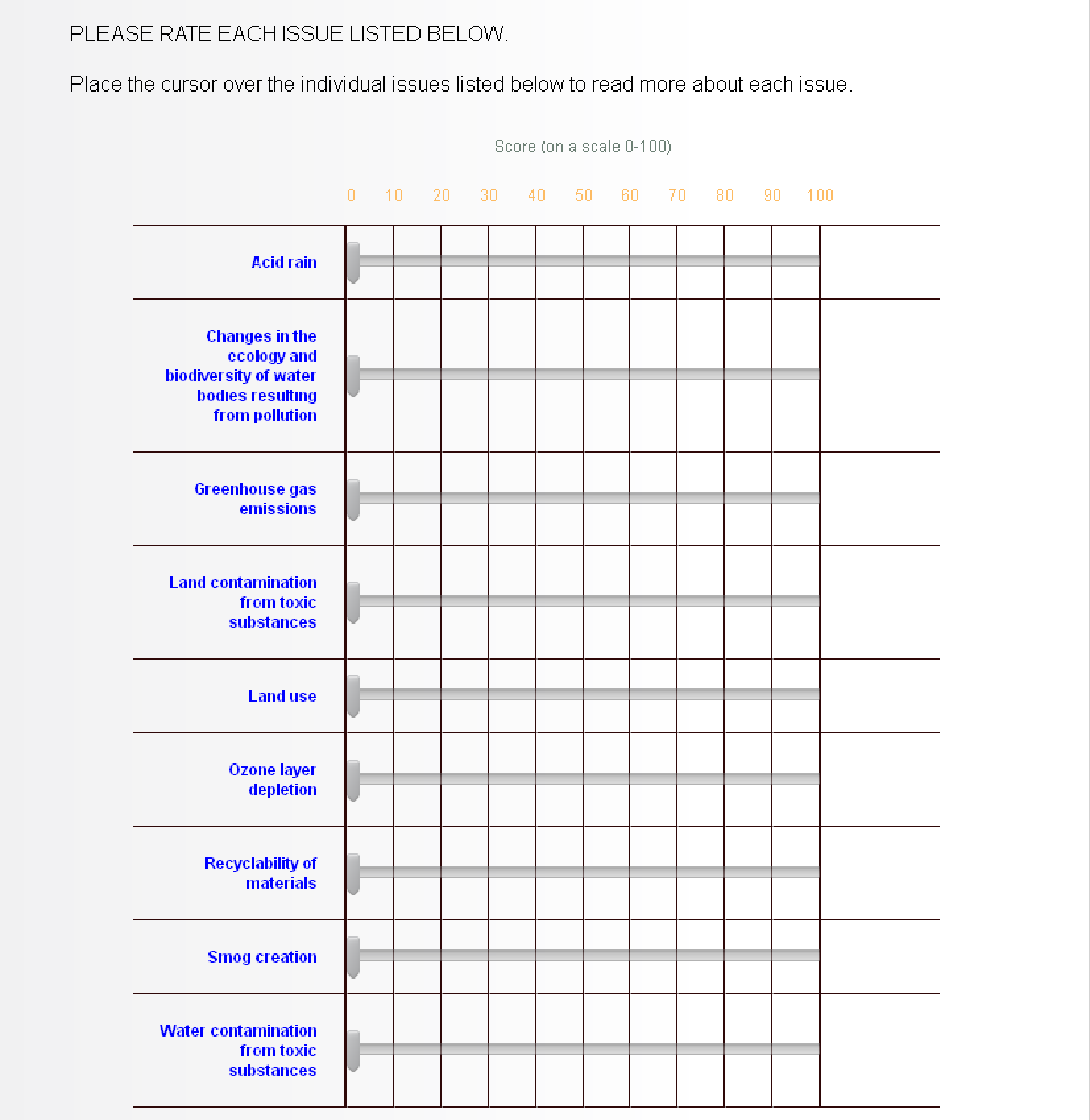
Reliable electricity generation

Q6 ENVIRONMENTAL ISSUES

Consider the environmental issues listed below. These issues are associated with the generation and provision of electricity. In your opinion, which environmental issues are the most important in evaluating and comparing different electricity-generating options?

Please indicate your preferences by following these instructions:

- assign the **most important** issue a score of **100** (do this by moving the score bar to 100 next to the chosen indicator);
- then assign each subsequent issue to a position on the scale that you think represents its relative importance in relation to all the other issues (this could be any number between 100 and 0);
- assign issues that you consider equally important the same value.


PLEASE RATE EACH ISSUE LISTED BELOW.

Place the cursor over the individual issues listed below to read more about each issue.

Score (on a scale 0-100)

Acid rain

Changes in the ecology and biodiversity of water bodies resulting from pollution

Greenhouse gas emissions

Land contamination from toxic substances

Land use

Ozone layer depletion

Recyclability of materials

Smog creation

Water contamination from toxic substances

Q7 SOCIAL ISSUES

Consider the social issues listed below. These issues are associated with the generation and provision of electricity. In your opinion, which social issues are the most important in evaluating and comparing electricity-generating options?

Please indicate your preferences by following these instructions:

- assume a hypothetical scale of 0-100, with a value of 100 representing the most important and 0 representing the least important indicator;
- assign the **most important** issue a score of **100** (do this by moving the score bar to 100 next to the chosen indicator);

- then assign each subsequent indicator to a position on the scale that you think represents its relative importance in relation to all the other indicators (this could be any number between 100 and 0);
- assign indicators that you consider equally important the same value.

PLEASE RATE EACH ISSUE LISTED BELOW.

Place the cursor over the individual issues listed below to read more about each issue.

Score (on a scale 0-100)

0 10 20 30 40 50 60 70 80 90 100

Civilian fatalities due to large accidents

Employment

Human health impacts from radiation

Human health impacts from toxic substances (excluding radiation)

Human rights violations and corruption

Imports of fuels

Local community investment

Spread of nuclear weapons and technology

Waste management required by future generations

Worker fatalities from work-related

YOUR OPINION ON DIFFERENT SOURCES OF ELECTRICITY: RANKING SUSTAINABILITY ASPECTS

Q8 In your opinion, which aspect of sustainability – techno-economic, environmental or social – is the most important in the sustainability assessment of electricity-generating options?

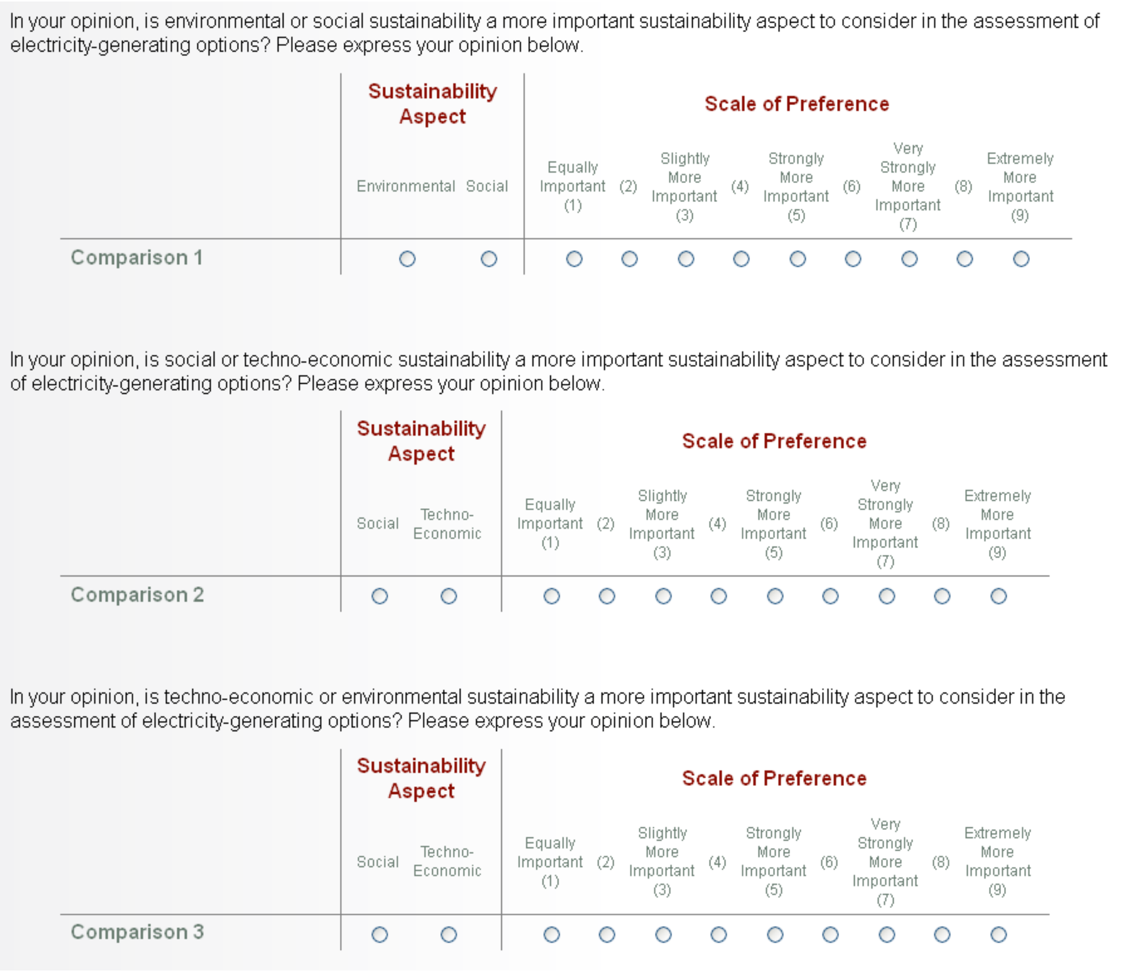
Please indicate your preferences by following these instructions:

- assume a scale of 1-9;
- consider two sustainability aspects at a time as shown in the tables below;
- indicate which sustainability aspect you consider to be more important in the first column; and
- assign an appropriate value between 1 and 9 (the scale is detailed below) to indicate how much more you prefer one sustainability aspect over the other.

1 = equally important
3 = slightly more important
5 = strongly more important
7 = very strongly more important
9 = extremely more important

Intermediate values of 2, 4, 6 and 8 may also be used.

PLEASE EXPRESS YOUR OPINION FOR EACH PAIR OF SUSTAINABILITY ASPECTS LISTED BELOW.



In your opinion, is environmental or social sustainability a more important sustainability aspect to consider in the assessment of electricity-generating options? Please express your opinion below.

	Sustainability Aspect		Scale of Preference								
	Environmental	Social	Equally Important (1)	(2)	Slightly More Important (3)	(4)	Strongly More Important (5)	(6)	Very Strongly More Important (7)	(8)	Extremely More Important (9)
Comparison 1	○	○	○	○	○	○	○	○	○	○	○

In your opinion, is social or techno-economic sustainability a more important sustainability aspect to consider in the assessment of electricity-generating options? Please express your opinion below.

	Sustainability Aspect		Scale of Preference								
	Social	Techno-Economic	Equally Important (1)	(2)	Slightly More Important (3)	(4)	Strongly More Important (5)	(6)	Very Strongly More Important (7)	(8)	Extremely More Important (9)
Comparison 2	○	○	○	○	○	○	○	○	○	○	○

In your opinion, is techno-economic or environmental sustainability a more important sustainability aspect to consider in the assessment of electricity-generating options? Please express your opinion below.

	Sustainability Aspect		Scale of Preference								
	Social	Techno-Economic	Equally Important (1)	(2)	Slightly More Important (3)	(4)	Strongly More Important (5)	(6)	Very Strongly More Important (7)	(8)	Extremely More Important (9)
Comparison 3	○	○	○	○	○	○	○	○	○	○	○

YOUR DETAILS

The final set of questions asks you about yourself to help us find out if there are any differences between the views of different groups of people.

ALL THE INFORMATION YOU PROVIDE ABOUT YOURSELF WILL BE KEPT STRICTLY CONFIDENTIAL.

Q9 PLEASE COMPLETE THE FOLLOWING:

Title:

Name:

Email address:

Daytime telephone number:

Which of these age groups are you in?

☐ 16-24
☐ 25-34
☐ 35-44
☐ 45-54
☐ 55-59
☐ 60-64
☐ 65-74
☐ 75+

Are you....

☐ Male
☐ Female

Please provide the **first half** of your postcode. This information will help us to find out if there are any differences in the opinions in different regions of the UK.

Would you like to be entered into the free prize draw?

☐ Yes
☐ No

Thank you very much for taking part in this survey and helping us with our research project.

19 Appendix 9 Description of Sustainability Issues for Public Survey 2

Civilian fatalities due to large accidents

Civilian deaths resulting from large accidents related to electricity generation.

Employment

Total employment created directly and indirectly by generation and provision of electricity.

Human health impacts from radiation

Human exposure to radiation can cause various health impacts, including radiation sickness and cancer.

Human health impacts from toxic substances (excluding radiation)

Toxic substances such as heavy metals emitted by some electricity-generating options may affect human health, including respiratory diseases and in some cases cancers.

Human rights violations and corruption

Sourcing of fuels or electricity from or involvement with countries with known corruption and human rights problems.

Imports of fuels

Avoiding fuel imports or importing from a greater number of countries rather than just one or two could help increase energy security. This can be achieved by increasing the use of energy sources in the UK and also by being able to store fuels for future use. Some fuels are more suited for storage (e.g. solid and liquid fuels) while others are less so (e.g. gaseous fuels).

Local community investment

This is investment that companies producing electricity may invest in local communities. This can include hiring staff from the local community, using local suppliers as well as building schools, hospitals etc.

Spread of nuclear weapons and technology

The potential for spread of nuclear weapons, radioactive material and/or weapons-applicable technology or information to politically unstable nations and regions.

Waste management required by future generations

This refers to the need to manage or store for a very long time toxic or dangerous waste generated by some energy technologies.

Worker fatalities from work-related accidents

This refers to work-related deaths associated with electricity generation.

Acid rain

Acid rain is caused by acid gases such as sulphur dioxide and nitrogen oxides emitted from combustion of some fuels used for electricity generation. Their precipitation causes acidification of waterways and land and can affect fish, vegetation and human health.

Greenhouse gas emissions

Greenhouse gases include carbon dioxide, methane and nitrous oxide. They can be emitted from different electricity-generating options and contribute to global warming and climate change.

Changes in the ecology and biodiversity of water bodies resulting from pollution

Plant biomass can become more highly concentrated in aquatic environments which have been polluted by certain substances (such as phosphates). This may then cause oxygen in the water body to become depleted. Negative environmental effects, such as reductions in the population size of some fish species and other water-dwelling animal species may then occur.

Land contamination from toxic substances

Toxic substances released to the environment can contaminate land and affect animals and plants.

Land use

Certain electricity-generating technologies may occupy greater areas of land than other throughout the lifetime of their operation, meaning that this land may not be used for other commercial or recreational activities. In addition, new plants or installations may need to be built on Greenfield (previously undeveloped) land due to increasing demands for land.

Ozone layer depletion

Depletion of the ozone layer is caused by CFCs which are used as refrigerants. The ozone layer protects us from the ultraviolet (UV) radiation from the Sun. Increased UV radiation can cause skin cancer.

Recyclability of materials

The potential recyclability of power plant components once decommissioned (scrapped).

Smog creation

Certain gases emitted into the atmosphere, such as volatile organic compounds and nitrogen oxides may react with sunlight to produce low-level ozone or so called “summer” smog. The smog may affect air quality, human health and vegetation.

Water contamination from toxic substances

Toxic substances released to the environment can contaminate rivers, lakes and oceans and affect aquatic organisms.

Cost of electricity

Cost of electricity generation related to the price which consumers pay for electricity.

Financial support from Government for various electricity-generating options

The Government may provide financial support to certain methods of electricity-generation through subsidies or other economic incentives. This assistance is usually provided to low carbon technologies in order to encourage electricity-generation from renewable and low-carbon sources.

Construction time taken for power stations

The total time taken before power plants can start to generate electricity.

Ability of plants to adapt to changing energy needs in the future

The ability of power plants to adapt to changing energy needs in the future. For example, plants which in addition to electricity can provide heating, produce hydrogen and/or be carbon neutral.

Reliable electricity generation

Some technologies provide a more stable output of electricity whilst others are less reliable due to the intermittent availability of their source of energy. Technologies with a more stable output can also respond better to peak demand for electricity (for example, in the evening due to cooking, watching television, etc.).

Depletion of world fuel reserves

This is related to the amount of fossil (coal, gas, oil) and nuclear (uranium) fuels remaining available for electricity generation.

20 Appendix 10 Descriptions of the Technologies Considered as Part of the Sustainability Assessment

20.1 An Overview of Carbon Capture and Storage Technologies

20.1.1 CO_2 capture technologies

The aim of the CO_2 capture process is to produce a concentrated stream of CO_2 from the emissions of fossil fuels or biomass (resulting in negative direct CO_2 emissions), which may then be transported and stored for indefinite periods of time in order to mitigate anthropogenic climate change. There are three main types of CO_2 capture that will be implemented commercially in the UK and internationally. These are: post-combustion capture, pre-combustion capture and oxy-fuel capture. Each of these methods is explained below.

20.1.1.1 Post-combustion capture

In post-combustion capture, CO_2 is removed from flue gasses after combustion of the fuel (fossil fuels or biomass). Figure 20.1 shows the basic processes involved in post combustion capture of CO_2, the fuel is combusted in air, and the flue gas resulting from the combustion has a much lower concentration of CO_2 (Figueroa *et al.*, 2008). A typical type of plant that would potentially employ post-combustion capture is a pulverised coal plant (Yang *et al.*, 2008). Post-combustion capture has the most potential for retro-fitting to older plants as the process treats the flue gas after combustion, so can be added as a process step without serious alteration of the prior combustion steps (Figueroa *et al.*, 2008). To capture of CO_2 from the flue gas in post-combustion there is one mature technique using amines solvents, and several novel processes that are in development.

20.1.1.1.1 Amine solvents

There are various proprietary amine-type solvents available and more are being developed as the specific properties must be tailored to the demands of CCS. This requires high capture for a low energy penalty, and low levels of impurity (IPCC 2005). The basic principal of the amine capture system is the absorption of CO_2 from the gas stream using amine solvents in a reaction column, the amine solvent absorbs the CO_2 and the resulting compound is soluble in water (IPCC 2005). To capture the CO_2 the amine solvent is sprayed into the gas stream in the reaction column, a water wash then captures the CO_2 rich compound. The resulting liquid is then reheated elsewhere and the CO_2 is released from the amine solvent and captured. This CO_2-depleted solvent can then be reused in the reaction column (IPCC 2005). Amines degrade over time due to impurities in the flue gas stream, and this is one of the costs and environmental-impact wastes produced in the system (IPCC 2005). A typical amine solvent is monoethanolamine (MEA). However, there are numerous alternatives under development and various additives that can improve the reaction.

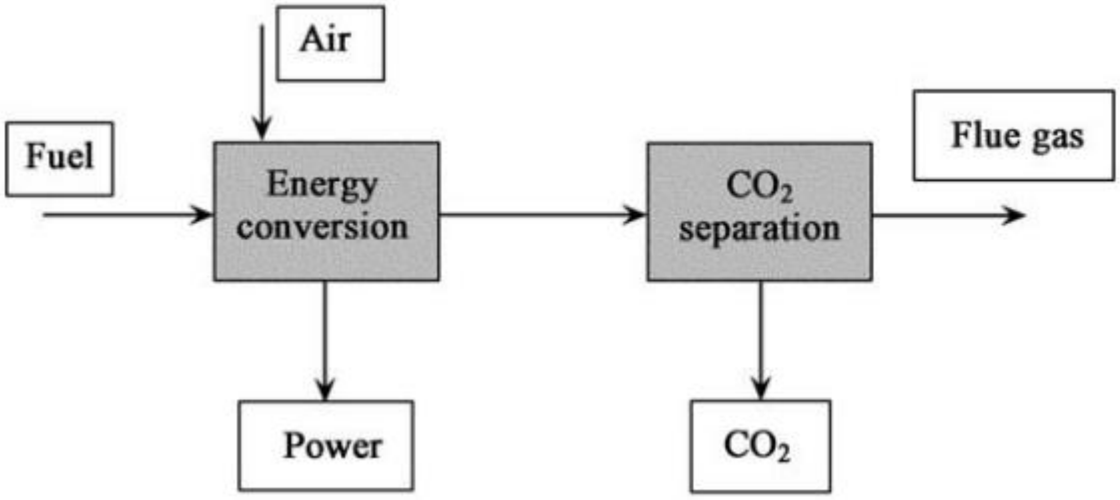


Figure 20.1. Schematic diagram of the processes involved in post-combustion capture. Fuel and air are used in the combustion step to convert chemical energy to electrical power, the resulting emissions from combustion are then treated and the CO_2 is separated from the flue gas stream. From Yang *et al.* (2008).

20.1.1.1.2 Techniques in development

Carbonate systems are one alternative option for CO_2 capture, conversion to bicarbonate captures CO_2 and subsequent heating releases it, which is less than the required heat for amines to release CO_2. A system developed at the University of Austin uses K_2CO_3 and a catalyst and has a 5% lower energy penalty (Figueroa *et al.*, 2008). Ammonia systems are another option and act in a similar way to amines, but they degrade less and have higher capacities, although they are potentially more volatile. Membrane technology has also been proposed in conjunction with amines - the membrane selectively filters out pollutants that can degrade the amine (Figueroa *et al.*, 2008). Other interesting avenues of work include metal-organic frameworks with CO_2 absorbing cavities, enzyme based systems, and ionic liquids.

20.1.1.2 Pre-combustion capture

Figure 20.2 displays the process steps carried out in pre-combustion capture. The fuel is gasified and a syngas is formed this consists of CO and H_2. The CO is reacted in a water shift reactor to create more H_2 and CO_2. The hydrogen rich fuel created can then be used to generate electricity or for other purposes after separation of the CO_2 (IPCC 2005). An example of this process in electricity generation is the IGCC (integrated basified combined cycle) coal power station, where coal is gasified and the gas fuel is burned in a gas turbine (Yang *et al.,* 2008). Solvent absorption (as discussed above) can be used to capture the CO_2 form the concentrated gas stream, and the flue gas is at a high concentration so the process is more efficient (Yang *et al.,* 2008). Physical solvents can also be used using pressure swing absorption due to the high partial pressure from the pre-combustion process - the physical solvent absorbs CO_2 at a high pressure and regenerates it at a lower pressure. Types of physical solvent include commercial solvents such as Selexol and Rectisol, and propylene carbonate (Figueroa *et al.*, 2008). Pre-combustion sorbents which absorb CO_2 from the syngas and also promote the water shift gas reaction are being developed, and include substances such as Li_4SiO_4 , along with membrane technology in conjunction with ionic fluids (Figueroa *et al.,* 2008).

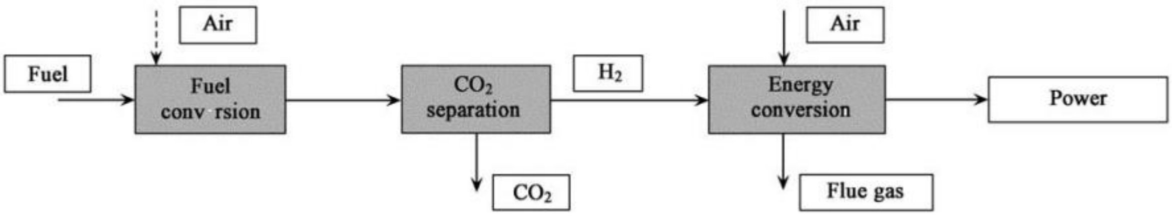


Figure 20.2. Schematic process diagram of pre-combustion capture. The fuel is gasified in the fuel conversion step; the CO2 is then separated from the gas formed leaving hydrogen, which is used as the fuel. This produces a flue gas with very different properties to post-combustion capture. From Yang *et al.* (2008).

20.1.1.3 Oxy-fuel combustion capture

Figure 20.3 shows the processes involved in oxy-fuel combustion. Oxy-fuel combustion modifies the flue gases by burning the fuel in pure oxygen, this produces a high concentration CO_2 flue gas stream (around 90%) which does not require separation techniques to remove the CO_2. This is highly advantageous in terms of the lack of requirement for solvent and membranes and other energy intensive processes (Yang *et al.*, 2008). However the process does require the cryogenic separation of oxygen which is energy intensive (although the furnace used burns at high temperatures) and development of new equipment is required. SO_2 removal is still also needed (Figueroa, *et al.*, 2008).

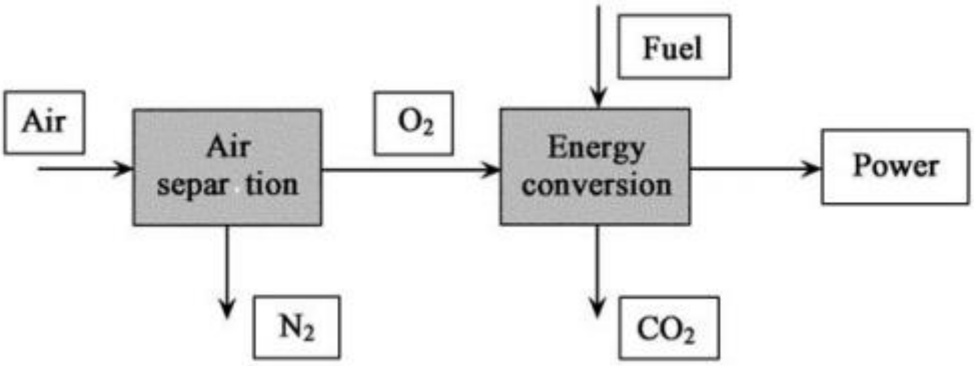


Figure 20.3. Oxy-fuel combustion - nitrogen is removed from air to leave a high concentration oxygen stream, when mixed with fuel and burned a high concentration CO_2 is produced as the flue gas. From Yang *et al.* (2008).

20.1.2 CO_2 transport

Generally, large point sources of CO_2 emissions are not located next to ideal storage locations for the CO_2 and this necessitates some form of CO_2 transport. In the UK this is a particularly pertinent point as the best storage options are in offshore locations. The four proposed options for CO_2 transport are: pipelines (both on and offshore); shipping; and road and rail transport. CO_2 pipelines are already in operation in North America for oil recovery operations, and shipping is routinely used to transport other gases such as LPG and LNG. Road and rail transport are also used to transport a wide range of gases. Pipelines are often seen as the favoured option for carbon capture and storage - unlike road and rail transport they are capable of transporting large volumes in a continuous stream. Cost estimates also suggest they are cheaper than shipping for all but the longest transport distances (IPCC 2005). CO_2 is transported in pipelines at ambient temperatures and pressures above 8MPa, this ensures that the CO_2 is in the dense phase and does not flow in a two-phase regime, which causes problems with pipeline operation and it also increases the density of the CO_2 making it cheaper and more convenient to transport (IPCC 2005). The most significant consideration of the transport stage for CO_2 storage is the pressure and temperature of the CO_2 as it reaches storage. The CO_2 will be in the dense phase, which will have implications for flow throughout the reservoir, and the behaviour of the CO_2 post injection. The CO_2 will be at surface temperatures, and possibly cool due to iso-caloric decompression of the gas as it enters the storage reservoir - this can lead to thermo-mechanical effects in the rock such as elastic stressing and lowering of the rocks fracture pressure (IEAGHG, 2011). Currently, the temperature effects are not fully understood, and both the temperature and pressure of the CO_2 entering storage are important considerations in development of CO_2 storage.

20.1.3 CO_2 storage

There are several proposed options for storage of CO_2, including mineral carbonation and ocean storage, however geological storage represents the option that is closest to market, has the most industrially related experience and is the most practical in terms of immediate environmental and logistical concerns. The general principle behind geological storage is to inject CO_2 in the dense phase into deep geological formations that have significant storage space in the pore spaces in the rock. The design of the storage solution is such that there is at least one mechanism of long-term immobilisation of the CO_2, and generally the depth, and therefore pressures and temperature, of the storage formation is chosen to maximise the storage space available by maintaining the dense state of the CO_2. The geological storage solution utilises natural formations, but the requirement to satisfy capacity, injectivity and storage security constraints dictate the choice of storage location and the techniques for injection and long-term storage management. The final engineered storage solution will include:

- trapping mechanism/s – e.g. impermeable cap rock seal or engineered residual trapping;
- significant capacity – usually through high permeability/porosity, this can be natural or artificially engineered;

- long-term storage security – on-going storage operations and natural phenomena will not compromise storage security and produce leakage.

The options for storage location generally fall into four categories:

- storage in depleted hydrocarbon reservoirs: oil and gas reservoirs;
- storage in deep un-mineable coal seams; and
- storage in saline aquifers.

For all cases, except storage in saline aquifers, the combination of storage operations with the recovery of fossil fuels is also possible. When a hydrocarbon reservoir is considered for storage operation the reservoir will be depleted of hydrocarbons to the maximum economic extent to allow the greatest capacity of CO_2 injection and minimise indefinite loss of hydrocarbon reserves. A concept often attached to considerations of CCS storage is the ability to employ enhanced oil recovery (EOR) and enhanced gas recovery (EGR), where the CO_2 injection improves the recovery of hydrocarbons whilst also storing CO_2. Storage in un-mineable coals seems allows a similar recovery of coal bed methane (CBM) based on the preferential adsorption of CO_2 onto the carbonaceous macerals of coal, thus displacing the methane gas (Holloway 2008).

20.2 An Overview of Fast Breeder Reactor Technology

A Fast Breeder Reactor (FBR) differs from thermal nuclear power reactors because the fuel is not moderated (as it is in thermal reactors), meaning that the neutrons emitted from the nuclear fuel can travel at speeds of around 1 MeV – although fast neutrons produced due to nuclear fission travel at a speed of around 2 MeV. Thermal neutrons travel at a speed of around 0.25 eV and are slowed down in the nuclear reactor by a moderator – a medium in the nuclear fuel such as heavy water, light water or graphite. The breeding ratio of the fissile nuclei must be more than 1 more nuclear fuel to be produced than is used. Fast reactors can use the U-238 in the nuclear fuel in addition to the fissionable U-235, and in addition will burn long-lived actinides within the nuclear fuel that would otherwise have to be stored as nuclear waste.

FBRs have been in operation around the world in a commercial capacity as well as for experimental and demonstrative purposes. However, the number of FBR's in commercial operation compared to the number of thermal reactors is very small. Their superior fuel economy make FBR's an attractive option for future civil nuclear development. However, as uranium fuel is a small proportion of the total cost of the nuclear fuel cycle, operation, decommissioning of the nuclear power plant and waste storage, meaning that the incentive for building FBRs (especially as they are relatively expensive to build) is minimised. In addition, FBRs are expensive to construct compared to thermal reactors and concern centred on nuclear proliferation of weapons in a closed fuel cycle is increased due to the reprocessing of (and increase in) plutonium from operation in FBRs (WNA, 2012b).

20.3 An Overview of the AP1000 and European Pressurised Reactor Designs

The AP1000 nuclear reactor (designed by Westinghouse) and the European Pressurised Reactor (EPR – designed by Areva and Electricite de France), are Generation III+ reactors which are currently both undergoing the UK's Generic Design Assessment (GDA) process. The AP1000 and the EPR are evolutionary Pressurised Water Reactors (PWR) that exhibit improved efficiency, safety, economics and levels of waste production compared to Generation II and III designs. The remainder of this section reviews the state of AP1000 and EPR development in the Health and Safety Executive (HSE) and Environment Agency's (EA) GDA process and considers the technological development of the AP1000 and EPR from the previous generations of nuclear reactors.

20.3.1 AP1000 reactor technology – innovations for Generation III+

The AP1000 (Advanced Passive) nuclear reactor designed by Westinghouse is a two-loop Pressurised Water Reactor (PWR) and an evolutionary upgrade from its AP600 reactor. The unique selling points of the AP1000 reactor include its attractive economics compared to previous generations of nuclear plants, increased safety, simplification of design and reliability (Schulz, 2006).

20.3.1.1 Primary equipment and reactor design

The reactor coolant system (RCS) of the AP1000 consists of two primary coolant loops, a reduction from four with other PWR designs. Each loop contains a steam generator, two reactor coolant pumps, one hot leg and two cold legs between which the coolant circulates from the reactor and the steam generators. (Schulz, 2006).

The AP1000 has a reactor power of 3400 MWt and a net electrical output of 1117 MWe (Sculz, 2006). Fuel performance has been upgraded from previous generations of PWRs through longer burn-up features of 60 GWd/te (Westinghouse, 2007a) and a higher-power density core of 157 fuel assemblies (in a 17 x 17 arrangement). The AP1000 can use fuel that is enriched by up to 4.8% UO_2, and it has an 18 month fuel cycle (Westinghouse, 2007a). The AP1000 would be enabled to accept up to 100% MOX fuel (which would impact on the sustainability assessment of this reactor), although the HSE have confirmed that the GDA is not considering this type of fuel in its assessment (HSE, 2009a).

20.3.1.2 Safety

The most conspicuous innovation of the AP1000 is the change in safety system to include passive safety features (and also passive residual heat removal and passive containment cooling) (Schulz, 2006). Electricity is not required for the system and operator input is greatly reduced. The reactor is simplified which reduces materials and equipment usually used in safety systems such as pumps, fans, chillers and rotating machinery. The simplification also means that operation and maintenance of the system is simplified too (Schulz, 2006). The system relies on natural forces such as gravity, natural circulation and compressed gas simple physical principles. The passive safety system is aligned by valves, most of which are ‘fail safe’. These valves require a loss of power in order to open to their safety alignment (Schulz, 2006). The passive safety system includes the following features: emergency core cooling system; safety injection and depressurisation; passive residual heat removal; and passive containment cooling system, all of which are explained below and displayed in Figure 20.4.

20.3.1.2.1 Emergency core cooling system

The emergency core cooling system protects the plant against leaks and ruptures from the reactor coolant system. If such events occur, the emergency core cooling system removes residual heat and depressurises the reactor core (Schulz, 2006).

20.3.1.2.2 Safety injection and depressurisation

Three sources of water are used by the emergency core cooling system in order to cool through safety-injection. These sources are the core makeup tanks, the accumulators and the in-containment refuelling water storage tank (IRWST). The IRWST is designed at atmospheric pressure, therefore the reactor coolant system must be depressurised before injection from the tank can take place. Depressurisation occurs in four stages through the automatic depressurisation system (Schulz, 2006).

20.3.1.2.3 Passive residual heat removal

The passive residual heat removal system removes heat by heat a heat exchanger. This protects the plant in the case that the feedwater or steam systems lines break. The IRWST provides the heat sink for the passive residual heat removal heat exchanger and can absorb heat for more than one hour before the water will begin to boil. After this happens, steam will pass to the containment where it will condense on the vessel and pass by gravity back to the IRWST. This is all provided with no operator input (Schulz, 2006).

20.3.1.2.4 Passive containment cooling system

The passive containment cooling system is the ultimate heat sink for the AP1000 plant. Following a nuclear accident, it will cool the containment so that design pressure is not exceeded and will be rapidly reduced. The steel containment vessel is the surface upon which the heat will be removed and transferred to the atmosphere by the convection of air within the vessel. This is also supplemented by water evaporation which is provided from a tank on top of the containment shield (Schulz, 2006).

20.3.1.3 Radioactive waste production and decommissioning

Waste management strategies have been supplied by Westinghouse to the HSE as part of the GDA process. Despite the HSE producing a report on Westinghouse’s design specifications for dealing with all types of radioactive waste (low-, intermediate- and high-level waste), the report provides not detailed account of the amounts of waste that are expected to be produced over the operational lifetime of the AP1000 reactor (HSE, 2009b). However, a CoRWM report (CoRWM, 2005) states that the AP1000 would produce 1.5

times as much spent fuel as the EPR, but produce 30% less intermediate-level waste and 20% less low-level waste over a 60-year life-span. The design of the AP1000 is such that less materials within the power plant will be exposed to less radiation over the operational lifetime of the plant, meaning that there will be less radioactive waste to deal with and also that there will potentially be more material recyclability of the plant upon decommissioning (Westinghouse, 2007b).

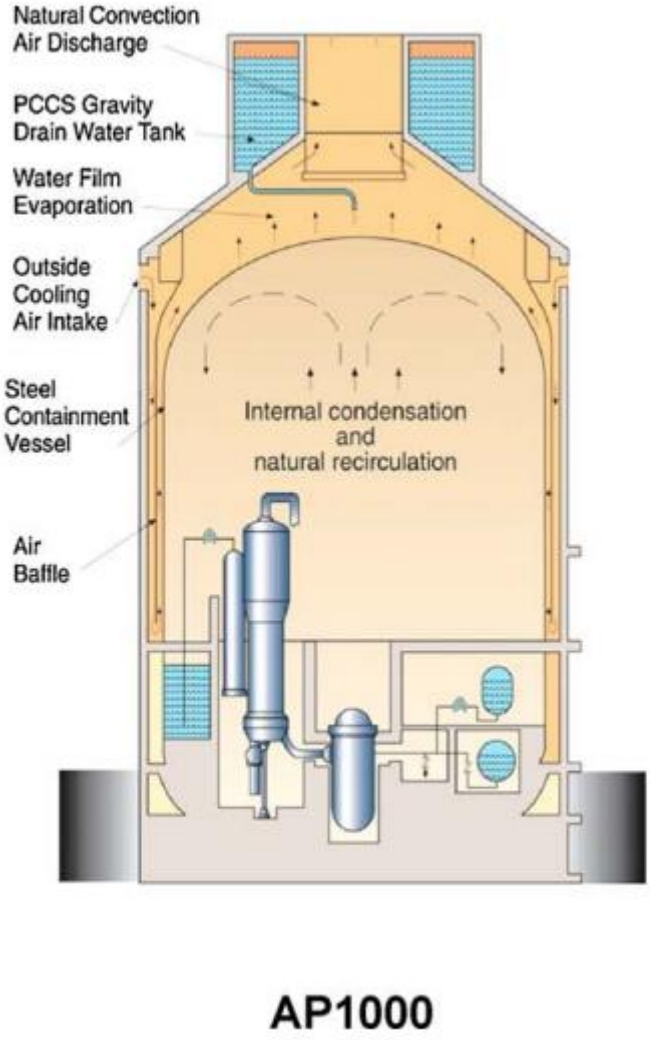


Figure 20.4. Schematic diagram of the AP1000 simplified safety systems. Taken from Schulz, 2006.

20.3.2 EPR reactor technology – innovations for Generation III+

The European Pressurised Reactor (EPR) is designed by Areva. The EPR differs from the AP1000 in that it is a four loop Pressurised Water Reactor (PWR) and an evolutionary upgrade from it's the Generation II French N4 and German Konovi reactors.

20.3.2.1 Primary equipment and reactor design

The EPR is similar to the SNUPPS design (Standardised Nuclear Unit Power Plant System) for PWRs developed by Westinghouse in the 1970s. The reactor vessel is surrounded by the four cooling loops, each with a hit leg which heated cooling water travels to the steam generator where the heat is transferred to the boiler water to generate steam. The coolant pumps then pump back cool water along the cold leg and back towards the reactor vessel (Areva NP and EDF, 2011a).

The EPR has reactor power of 4500 MWt and a net electrical output of 1660 MWe (WNA, 2012a). The EPR can use fuel that is enriched by up to 5% UO_2 and it has a flexible 18-24 month fuel cycle. It has the same burn-up as the AP1000 of 60GWd/te (Areva NP and EDF, 2011a). The fuel arrangement consists of 242 fuel assemblies in 17 x 17 fuel assembly.

20.3.2.2 Safety

The safety approach for the EPR is based on 'defence in depth', which comprises of a five-level layering of lines of defence to protect against human or technical failure (Areva NP and EDF, 2011b). This five-level structure consists of the following:

1) a combination of design quality assurance and control margins aimed at preventing the occurrence of abnormal operating conditions or plant failures;
2) implementation of protection devices which make it possible to detect and correct the effects of deviations from normal operation or the effects of system failures. This defence level is aimed at ensuring the integrity of fuel cladding and that of the primary cooling system so as to prevent accidents;
3) safeguard systems, protection devices and operating procedures which make it possible to control the consequences of accidents that may occur so as to contain radioactive material and prevent the occurrence of severe accidents;

4) measures aimed at preserving containment integrity and controlling severe accidents; and
5) all measures for protecting the public against the effects of significant radiological releases. Such measures for emergency control and on- and off-site emergency response are not directly linked with the generic design of a plant (Areva NP and EDF, 2011b).

The safety functions implemented in order to adhere to the ‘defence in depth’ approach include three main measures: control of fuel reactivity, fuel heat removal and containment of radioactive material. The fuel reactivity is maintained using the following measures: using a passive system of gravity insertion of rod cluster control, a heavy reflector which enhances neutron reflection in the fuel, monitoring of the core through the use of specified core parameters and use of a dedicated emergency boration system. Fuel heat removal will be achieved by using a safety injection system and shutdown cooling, separation of the steam generator auxiliary feedwater supply from the feedwater supply used in the start-up and shutdown (meaning that in result of failure of the pumps used within the main cooling system an emergency system will be able to provide back-up), installation of an emergency heat-removal system outside of the containment, improved design of the coolant system and a reduction in the sensitivity of the unavailability of reactor equipment. Finally, containment of radioactive material would be achieved by engineering a double-walled containment concept, which is designed to guarantee low leakage in the result of an accident. The space in-between the inner and outer wall is at negative pressure, meaning that any fluid leaked would be contained within the barrier (Areva NP and EDF, 2011b).

20.3.2.3 Radioactive waste production and decommissioning

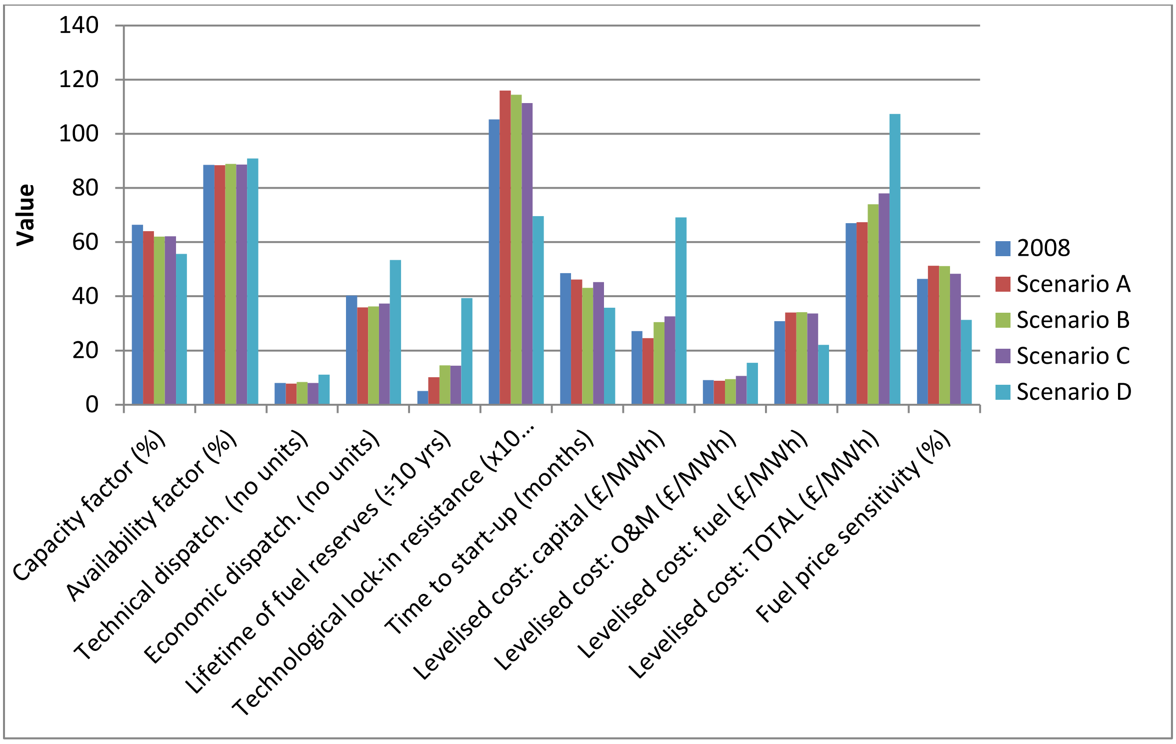
The EPR reactor has been designed in order to minimise the amounts of radioactive waste and spent nuclear fuel produced from operation. Areva and EDF’s report includes a chapter on discharges and waste resulting from operation of a Generation III+ EPR in the UK (Areva NP and EDF, 2011c). The chapter gives detail on waste arising from spent fuel, solid waste, liquid radioactive effluent, gaseous radioactive effluent and chemical effluent. For the purposes of this work, this section will only detail the data and information on the spent fuel and solid radioactive waste arisings.

Areva/EDF state in the report that the EPR makes better overall fuel use due to more efficient use of neutrons and increased operating and safety margins, this also reduces the amount of waste produced resulting from operation. Increased burn-up (65 GWd/tU) of the nuclear fuel is also a feature of the EPR and the reactor has the option of using up to 30% MOX fuel, although this practice is not currently implemented in the UK. The high burn-up rate in the EPR should mean that 7% savings on the amount of natural uranium used can be saved. The amount of plutonium produced during operation is also reduced by15% as plutonium is used in the during the fuel cycle and contributes to around 40% of the energy produced by the reactor.

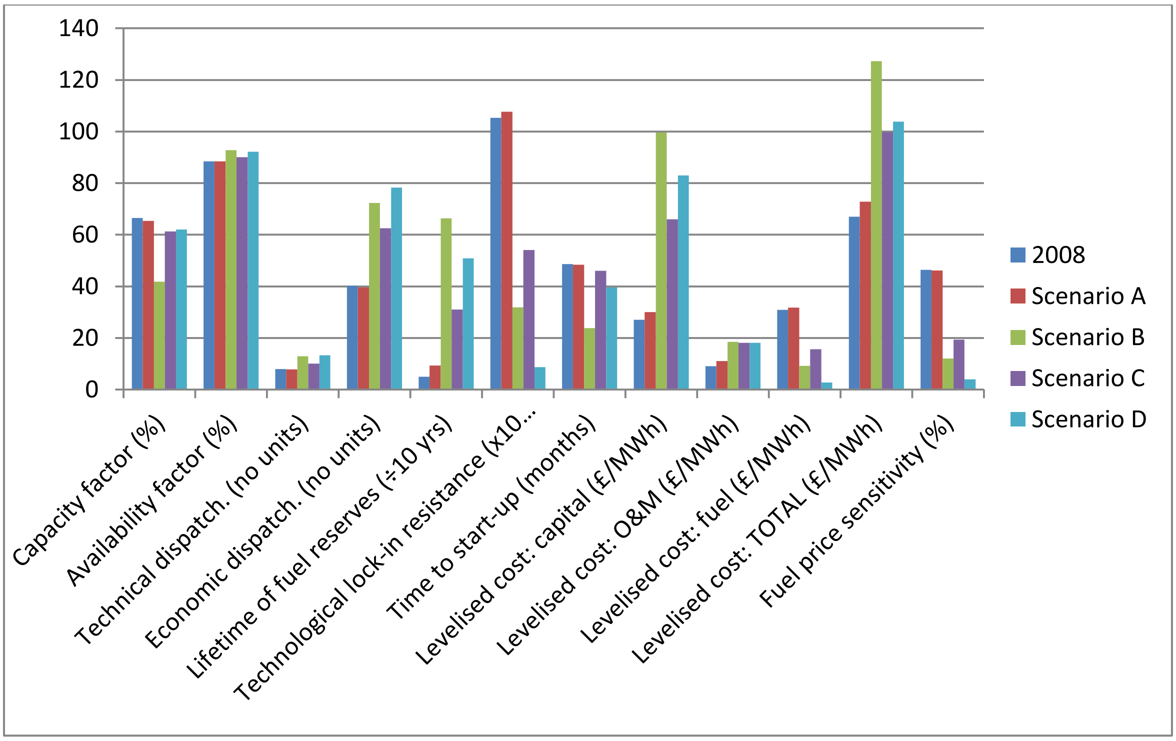
The annual estimated solid waste that would be produced from operation of the EPR would be around 80 m^3. The design principles of the reactor also outline the need of least production possible of radioactive waste and hazardous material (Areva NP and EDF, 2011d). The decommissioning stage of the plant’s life cycle is aimed to produce the least waste possible through recycling, re-use and decontamination of recyclable materials. Areva and EDF also aim to minimise the waste produced from equipment used to decommission the plant after its operational life. In order to achieve this, several measures will be put into place: choosing materials with less propensity to become radioactive; using shielding and barriers to minimise contamination of equipment and design of rooms and systems that do not aid the transportation of contamination (Areva NP and EDF, 2011d).

21 Appendix 11 Techno-Economic Impacts of Electricity Scenarios

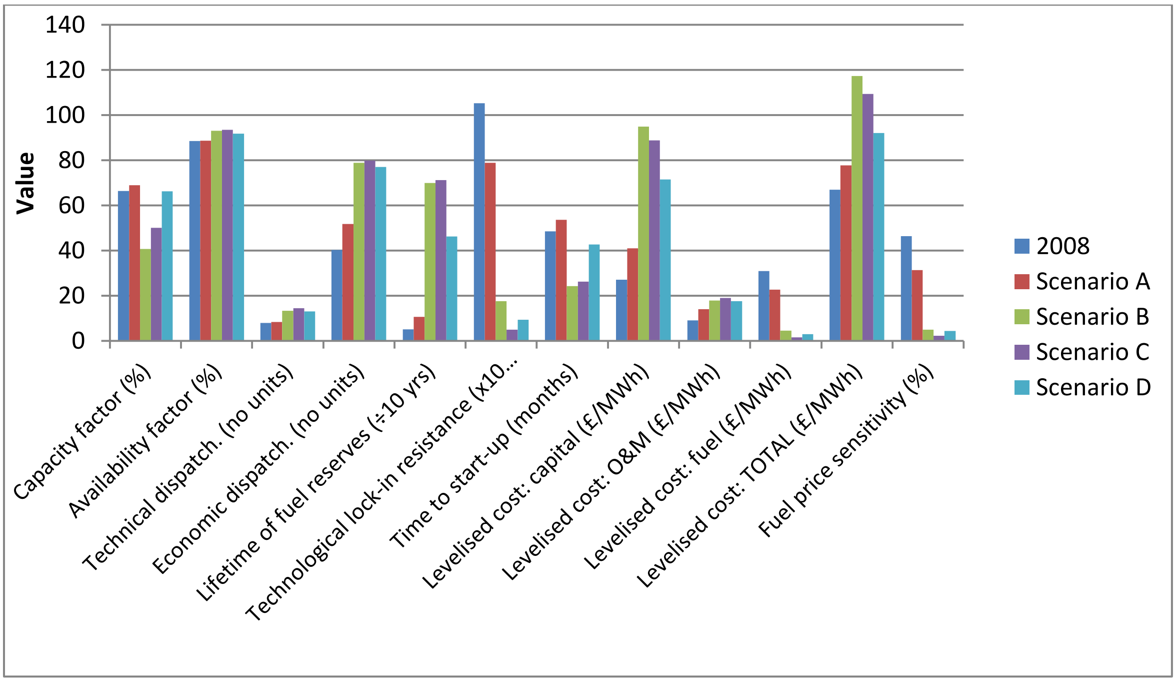
Year: 2020



Year: 2035

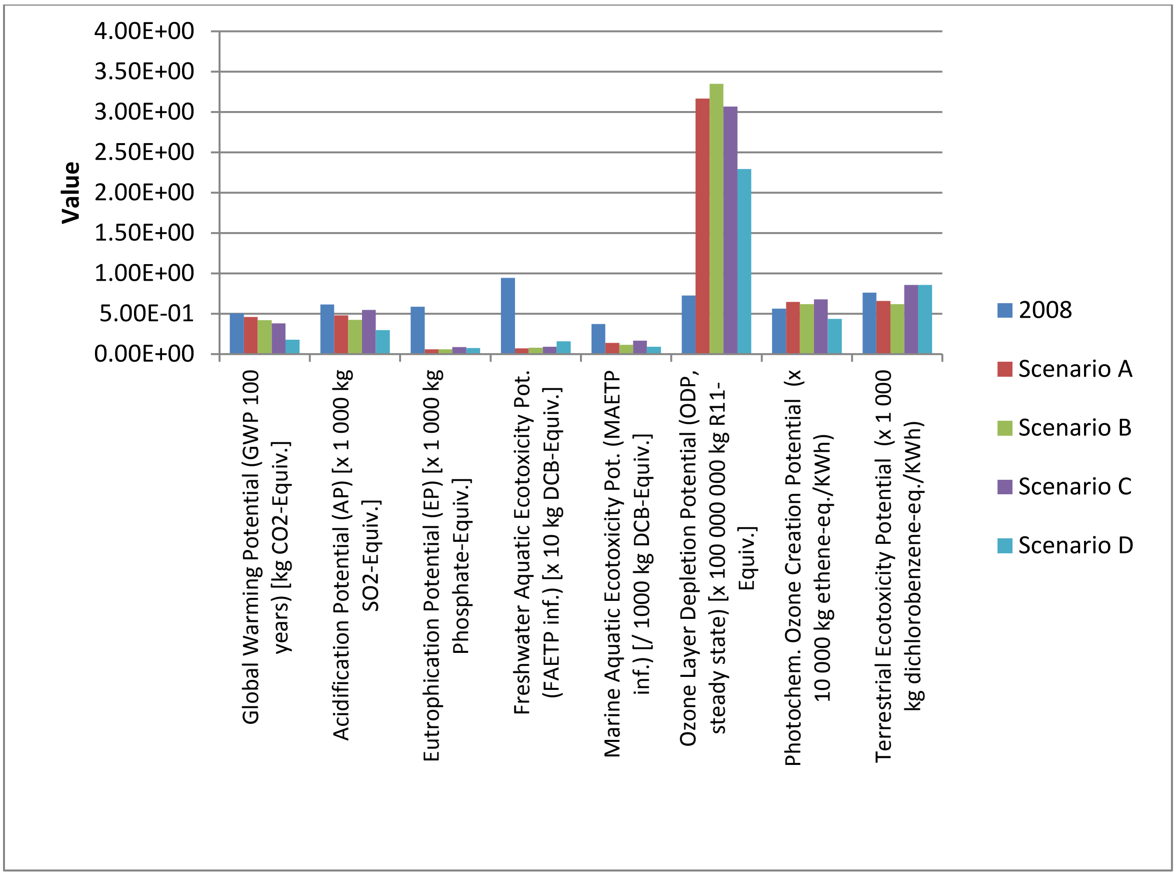


Year: 2050

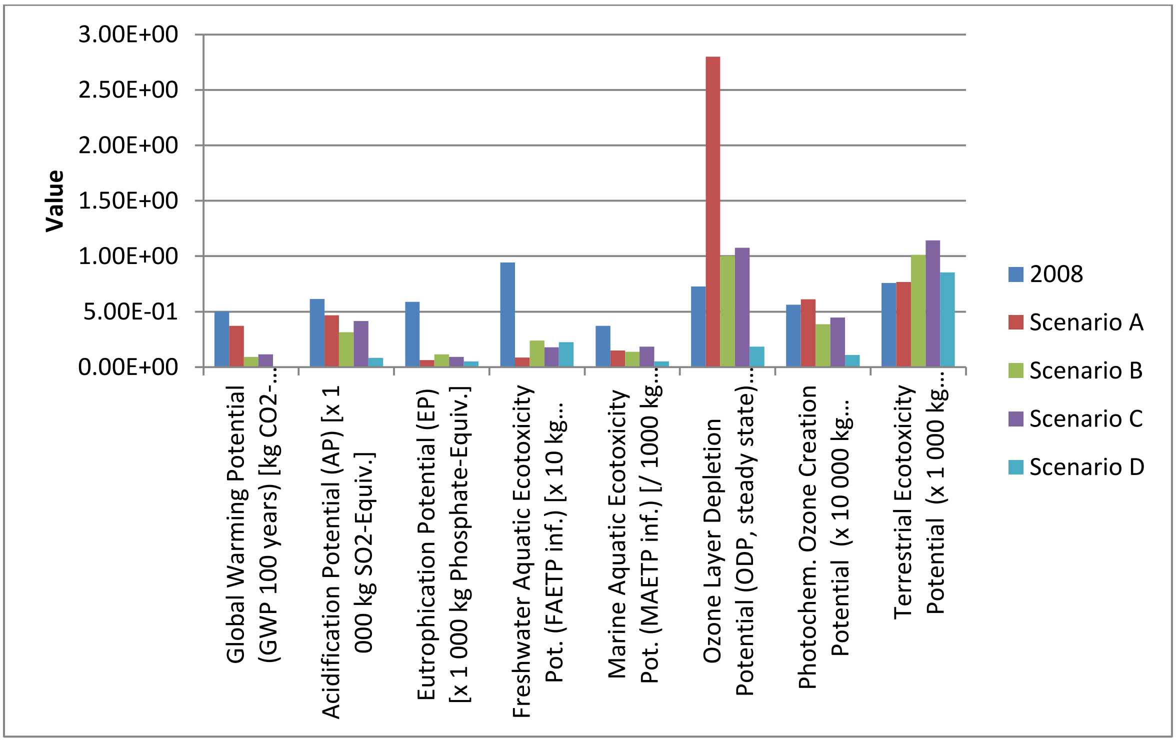

Value
140
120
100
80
60
40
20
0
Capacity factor (%)
Availability factor (%)
Technical dispatch. (no units)
Economic dispatch. (no units)
Lifetime of fuel reserves (÷10 yrs)
Technological lock-in resistance (x10…
Time to start-up (months)
Levelised cost: capital (£/MWh)
Levelised cost: O&M (£/MWh)
Levelised cost: fuel (£/MWh)
Levelised cost: TOTAL (£/MWh)
Fuel price sensitivity (%)
2008
Scenario A
Scenario B
Scenario C
Scenario D

22 Appendix 12 Environmental Impacts of Electricity Scenarios

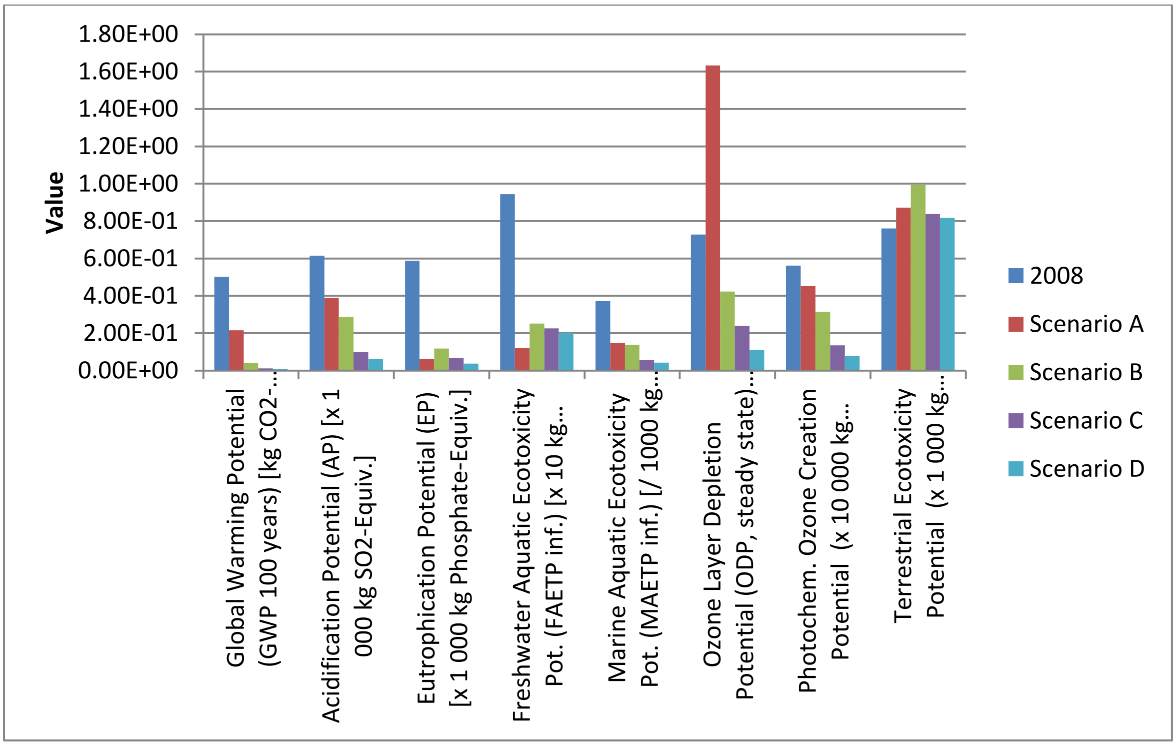
2020



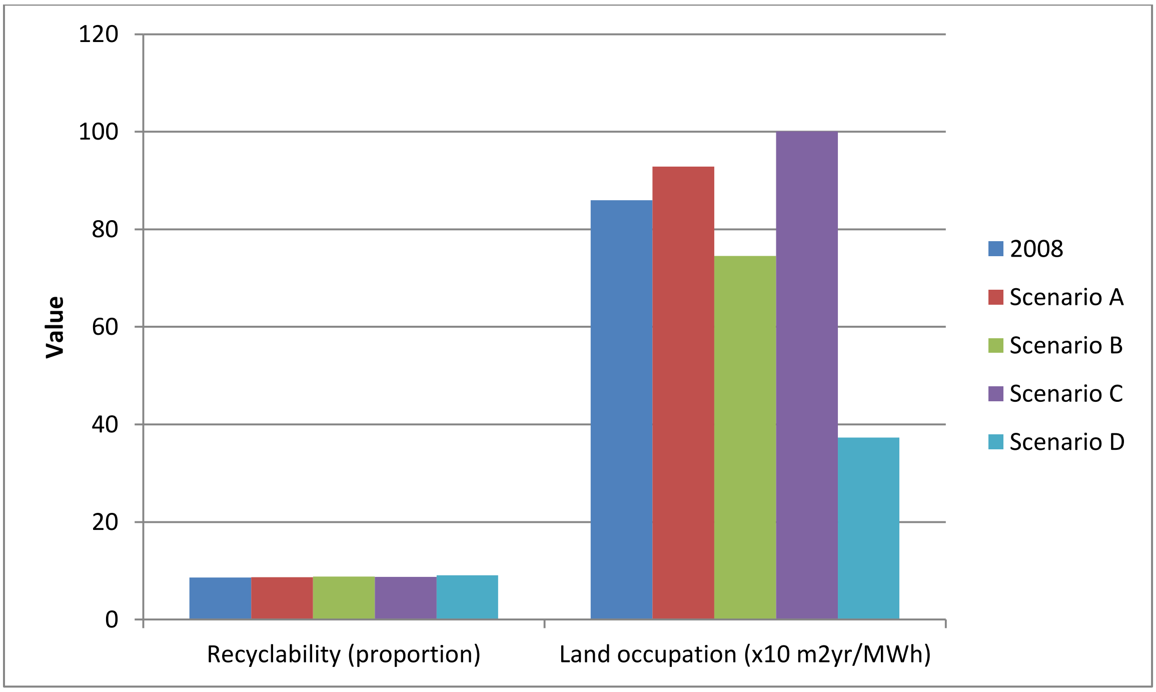
2035



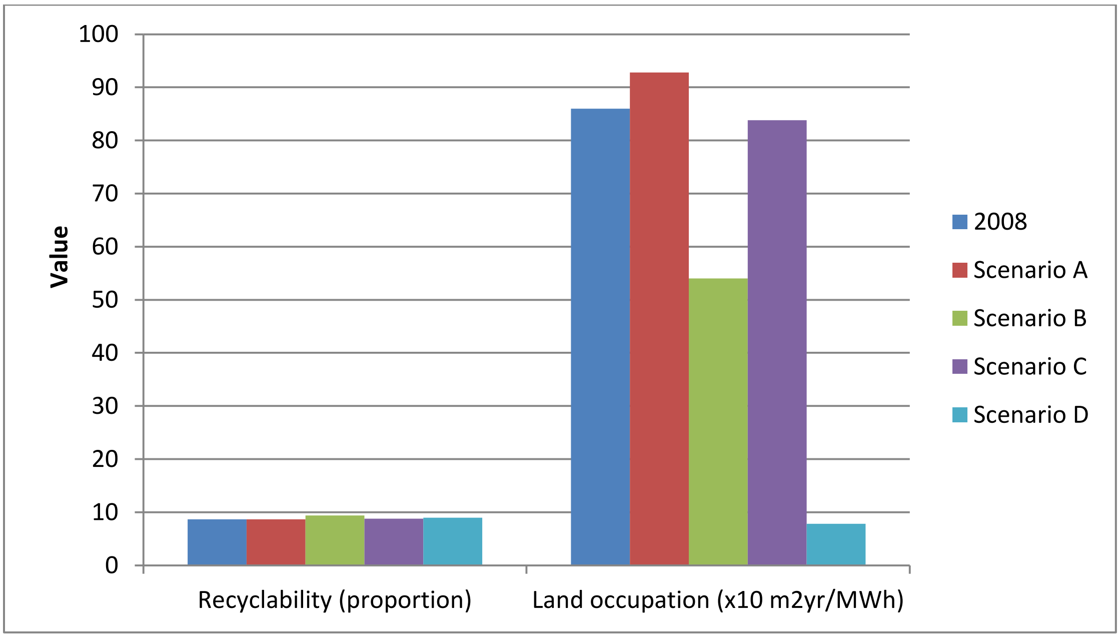
2050



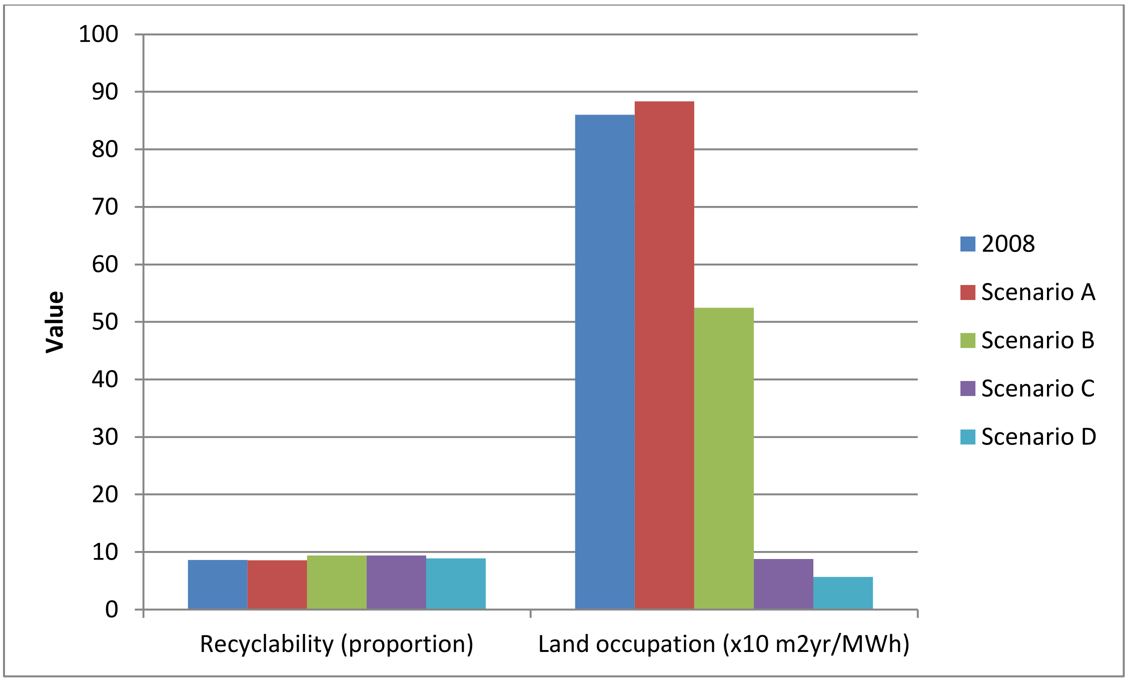
Recyclability and land occupation: 2020



Recyclability and land occupation: 2035

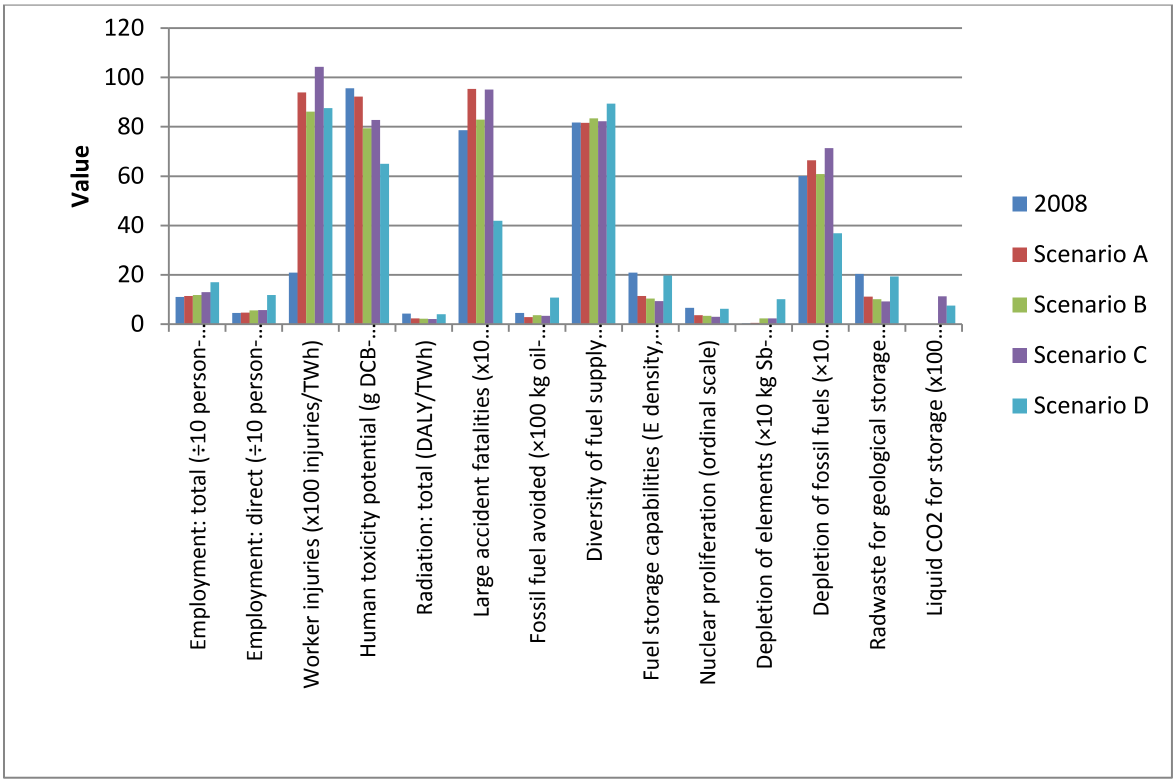


Recyclability and land occupation: 2050

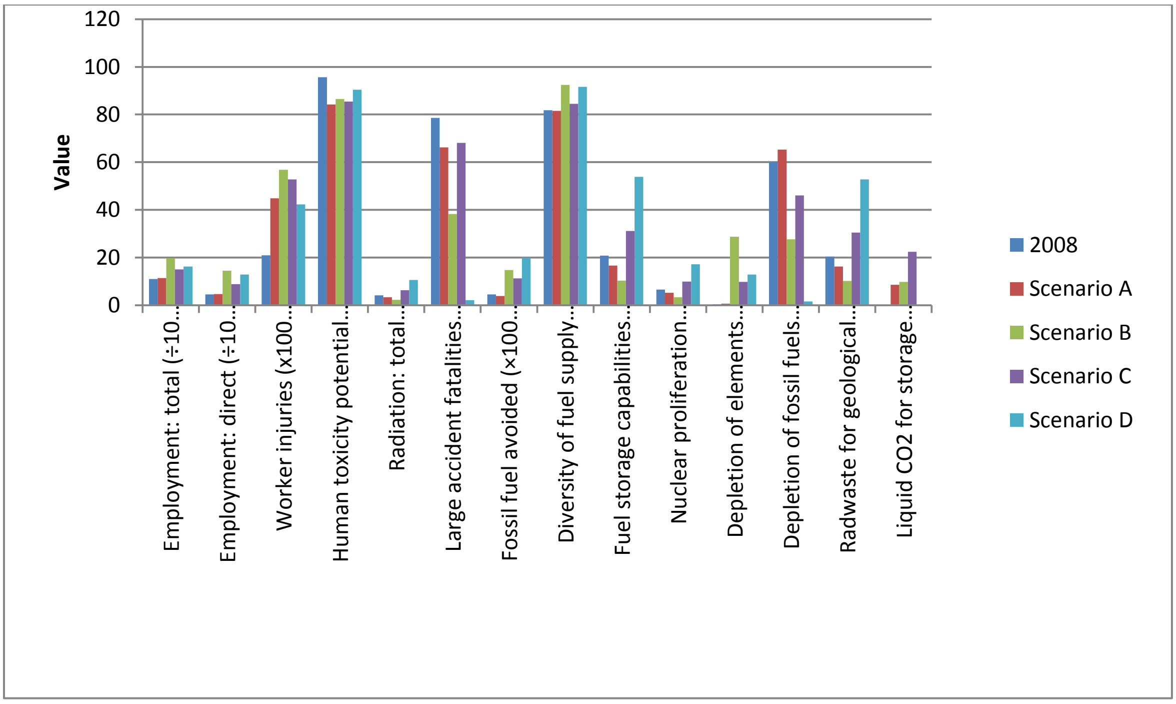


23 Appendix 13 Social Impacts of Electricity Scenarios

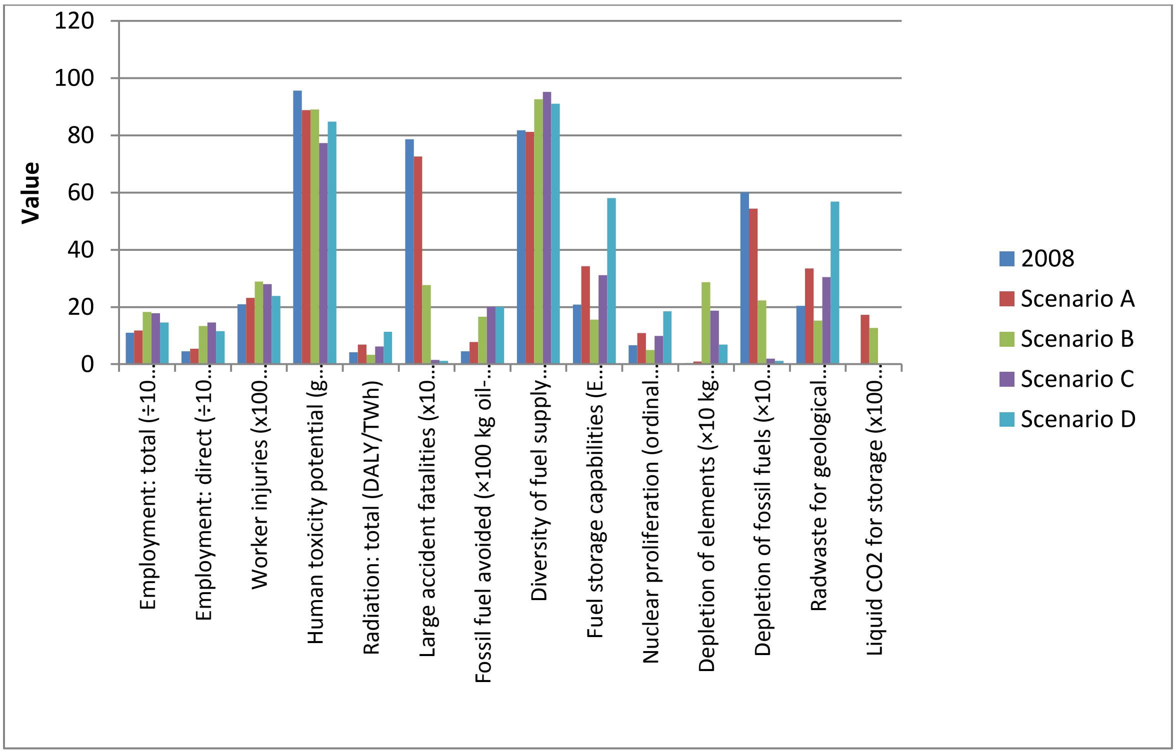
Year: 2020



Year: 2035



Year: 2050


Value
120
100
80
60
40
20
0
Employment: total (÷10…
Employment: direct (÷10…
Worker injuries (x100…
Human toxicity potential (g…
Radiation: total (DALY/TWh)
Large accident fatalities (x10…
Fossil fuel avoided (×100 kg oil-…
Diversity of fuel supply…
Fuel storage capabilities (E…
Nuclear proliferation (ordinal…
Depletion of elements (×10 kg…
Depletion of fossil fuels (×10…
Radwaste for geological…
Liquid CO2 for storage (x100…
2008
Scenario A
Scenario B
Scenario C
Scenario D