Life cycle sustainability assessment of electricity generation: a methodology and an application in the UK context

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AC	annualised cost
BOD	biological oxygen demand
Burnup	a measure of how much energy is extracted from the fuel in a nuclear reactor. It is normally expressed in gigawatt-days per tonne of heavy metal (GWd/t), where the energy output (gigawatt-days) refers to thermal rather than electrical energy.
BWR	boiling water reactor: a type of nuclear reactor using boiling water (either 'light' H_20 or 'heavy' D_20) as moderator and coolant.
CANDU	Canadian deuterium uranium reactor: a pressurized water reactor using heavy water (D_2O) as moderator and coolant. This decreases absorption of neutrons relative to LWRs, reducing or eliminating the need for uranium enrichment.
CCNG	combined cycle natural gas: see CCGT
CCGT	combined cycle gas turbine: a type of power station using natural gas to drive a gas turbine (Brayton cycle) whilst exploiting the resulting heat to produce steam to drive a steam turbine (Rankine cycle). This combined cycle greatly improves efficiency compared to a stand-alone gas turbine.
CCS	carbon capture and storage
CETP	China Energy Technology Program
CFC	chlorofluorocarbon
CML	Centrum voor Milieuwetenschappen Leiden (Leiden Institute of Environmental Sciences, the Netherlands)
DALY	disability-adjusted life years: a measure of loss of life and health in which the detriment of disease is weighted in order to express loss of health in terms of years of life lost.
GHG	greenhouse gas
GRI	Global Reporting Initiative
GWP	global warming potential
HC	hydrocarbon
HLW	high-level radioactive waste
HWR	heavy water reactor: a category of nuclear reactors that use heavy water (D_2O) as moderator and coolant.

IGCC	integrated gasification combined cycle: a coal power plant in which the coal is gasified before being passed through a gas turbine whilst simultaneously providing heat to produce steam for a steam turbine. Similar to a CCGT.
ILW	intermediate-level radioactive waste
IUCN	International Union for Conservation of Nature
LCA	life cycle assessment
LLW	low-level radioactive waste
LWR	light water reactor: a category of nuclear reactors that use normal water (H_2O) as moderator and coolant. PWR and BWR are types of LWR.
Man-Sv	man-sievert: a unit of collective effective radiation dose. It measures the average effective dose received by a group of people (in Sv), multiplied by the number of people.
MCDA	multi-criteria decision analysis
MOX	mixed oxide fuel: a type of nuclear fuel produced from reprocessed plutonium. MOX is a mixture of plutonium and uranium, as opposed to 'normal' fuel which does not contain plutonium.
NEA	Nuclear Energy Agency
NGCC	natural gas combined cycle (see CCGT)
NMVOC	non-methane volatile organic compound
NPV	net present value
OCGT	open cycle gas turbine: a gas turbine without the additional steam turbine of a CCGT. Less efficient than a CCGT but more able to quickly vary its power output.
OECD	Organisation for Economic Cooperation and Development
PM10	particulate matter measuring less than 10μm
PWR	pressurised water reactor: a type of nuclear reactor using light water (H_2O) as moderator and coolant under high pressure.
PV	photovoltaic
RO	renewable obligation order: the primary regulatory stimulus for uptake of large-scale renewable energy generation technologies in the UK.
ROC	renewable obligation certificate
VOC	volatile organic compound
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index

Sv, sievert	SI unit of effective radiation dose. A given dose of radiation, in Grays (J/kg), is adjusted based on the sensitivities of different organs to radiation. This is the effective dose, measured in sieverts (more often millisieverts, mSv).
toe	tonnes of oil equivalent
YOLL	years of life lost

Abstract

Life cycle sustainability assessment of electricity generation: a methodology and an application in the UK context

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This research has developed a novel sustainability assessment framework for electricity technologies and scenarios, taking into account techno-economic, environmental and social aspects. The methodology uses a life cycle approach and considers relevant sustainability impacts along the supply chain. The framework is generic and applicable to a range of electricity technologies and scenarios. To test the methodology, sustainability assessments have been carried out first for different technologies and then for a range of possible future electricity scenarios for the UK. The electricity options considered either contribute significantly to the current UK electricity mix or will play a greater role in the future; these are nuclear power (PWR), natural gas (CCGT), wind (offshore), solar (residential PV) and coal power (subcritical pulverised). The results show that no one technology is superior and that certain tradeoffs must be made. For example, nuclear and offshore wind power have the lowest life cycle environmental impacts, except for freshwater eco-toxicity for which gas is the best option; coal and gas are the cheapest options, but both have high global warming potential; PV has relatively low global warming potential but high cost, ozone layer and resource depletion. Nuclear, wind and PV increase certain aspects of energy security but introduce potential grid management problems; nuclear also poses complex risk and intergenerational questions.

Five potential future electricity mixes have also been examined within three overarching scenarios, spanning 2020 to 2070, and compared to the present-day UK grid. The scenarios have been guided by three different approaches to climate change: one future in which little action is taken to reduce CO_2 emissions ('65%'), one in which electricity decarbonises by 80% by 2050 in line with the UK's CO_2 reduction target ('80%'), and one in which electricity is virtually decarbonised (at the point of generation) by 2050, in line with current policy ('100%').

In order to examine the sustainability implications of these scenarios, the assessment results from the present-day comparison were projected forward to describe each technology in future time periods. Additional data were compiled so that coal with carbon capture and storage (CCS) – a potentially key future technology – could be included. The results of the scenario analyses show that the cost of generating electricity is likely to increase and become more capital-intensive. However, the lower-carbon scenarios are also at least 87% less sensitive to fuel price volatility. Higher penetration of nuclear and renewables generally leads to better environmental performance and more employment, but creates unknown energy storage costs and, in the case of nuclear power and coal CCS, the production of long-lived waste places a burden of management and risk on future generations.

Therefore, the choice of the 'most sustainable' electricity options now and in the future will depend crucially on the importance placed on different sustainability impacts; this should be acknowledged in future policy and decision making. A good compromise requires strategic government action; to provide guidance, specific recommendations are made for future government policy.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright statement

Dedication

In loving memory of my mother, Judith Oldham (1953-2012).

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During the course of this research I have been very lucky in having the chance to interact with many external organisations. I am extremely grateful to Dr David Ross and his colleagues at National Nuclear Laboratory (NNL) for the time they invested in our collaboration on data quality assessment for this project. I also kindly acknowledge the information and assistance given by Prof. Peter Burgherr and the Paul Scherrer Institut (PSI) regarding large accident fatality estimates. Over 30 additional organisations and SPRIng project partners also contributed their time and knowledge during the stakeholder feedback process by which the sustainability indicators developed in this project were refined.

Finally, I wish to thank my girlfriend and my family for the support and inspiration they have provided over the course of this work: it would not have been possible without them.

1 Introduction

Sustainable development has, as its key tenet, the concept of continuing prosperity for all people in both current and future generations [1]. Its relevance to the electricity sector is clear when we consider the ubiquity of electricity: as an extremely adaptable 'high-grade' energy source [2] it has become fundamental to virtually every aspect of modern life; commerce, government, households and many forms of recreation rely on it, and this reliance has increased considerably in the last four decades [3]. Indeed, it is set to increase further, principally due to changes in the transport sector, with projected trends in policy and vehicle production [see 4] pointing towards increasing adoption of battery- and hydrogen-powered vehicles, both of which depend on electricity.

In addition to this increase in demand, supply of electricity is also changing rapidly, nowhere more so than in the UK, as discussed below. It is extremely important, therefore, that more sustainable energy options are identified and pursued in order to maximise the welfare of society, environment and economy. To work towards this goal, the current electricity supply must first be considered.

1.1 Electricity in the UK

In the UK, approximately 380 TWh of electricity was generated in 2010, constituting 18% of total energy consumption and generating roughly a third of national CO_2 emissions [5]. The electricity sector is dominated by six large, vertically-integrated companies commonly referred to as the 'Big Six'[1] who, in 2010, accounted for 65% of electricity generation and 87% of total sales [6]. The UK's electricity mix, shown in Figure 1, is currently dominated by coal (28%), gas (47%) and nuclear (15%), with renewable sources (predominantly hydroelectricity and wind) playing a much smaller role (~7%) [5].

However, this mix is beginning to move away from the technologies that have dominated production for the past few decades. The EU Large Combustion Plant Directive [7], the UK's switch from net gas exporter to importer [5], the retirement of most of the nuclear fleet by 2023 [see 8] and the legally binding Climate Change Act [9] have all forced the government to consider

[1] Centrica, EDF Energy, E.ON UK, RWE npower, Scottish Power and SSE

important questions about replacing current capacity. In many cases (such as that of nuclear power), decisions taken today will dictate the future of the UK's electricity supply for 60 years or longer due to the long lifetimes of new power plants and their associated financial and infrastructural commitments.

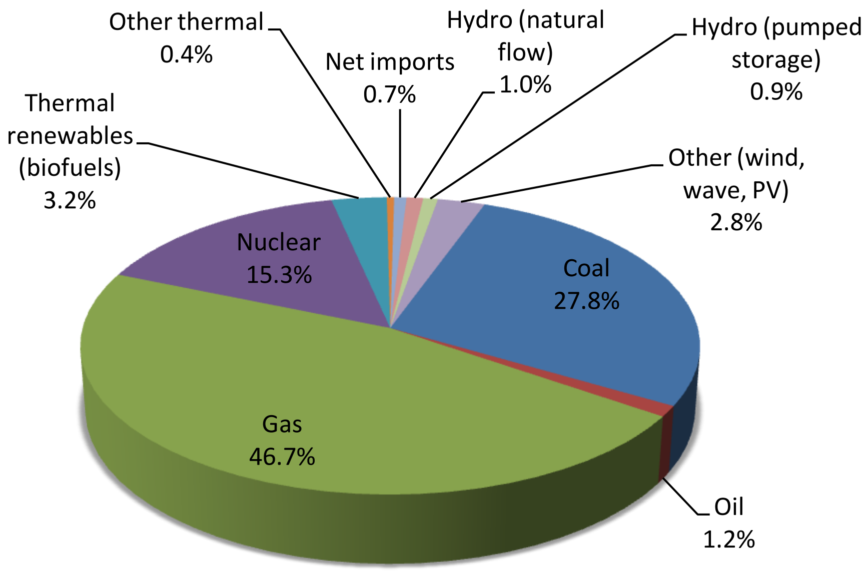


Figure 1: Breakdown of the UK electricity supply in 2010, by fuel type (based on data from [5]).

Of the changes taking place to the UK electricity mix, one of the most significant involves wind power, particularly offshore, with current policy aiming to increase substantially installed capacity. In December 2000, The Crown Estate began awarding sites in UK waters to potential wind farm developers and this process has continued in three 'rounds' of development, each successively larger than the last (although, at the time of writing, Rounds Two and Three are yet to be completed). The three rounds total a potential installed capacity of 33 GW [10]; roughly 25 times the capacity of operational offshore wind farms in the UK in 2011 [calculated from 11]. The scale of this expansion is reflected in the emphasis given to offshore wind in the Renewables Obligation [12] which functions as the main stimulus for renewable energy technologies in the UK: while many renewables, such as onshore wind and hydroelectricity, receive one Renewables Obligation Certificate (ROC) per MWh produced, offshore wind receives between 1.5 and 2 in order to attract investment by offsetting its relatively high costs. Between 2002 (when ROCs were introduced) and the start of 2012, UK offshore wind capacity increased almost 500-fold (calculated from [5] and [13]).

Another renewable option favoured in the UK is solar photovoltaics (PV). Since the introduction of the Feed-in Tariff (FiT) in April 2010, large energy suppliers have been required to make payments to owners of small-scale (<5 MW) renewable installations, such as PV, based on the total amount of electricity produced as well as exported to the grid [14]. Although PV, until recently, only supplied a tiny percentage of UK electricity (approximately 0.009% in 2010 [5]), in its first full year of operation, the FiT had resulted in 28,705 PV installations, totalling 78 MW [15]; this is more than triple the total installed capacity in 2009 [calculated from 16]. It seems, therefore, that PV is set to become a significant generating technology in the UK.

The Government is also trying to encourage new nuclear build, as exemplified in its recent National Policy Statement for Nuclear Power Generation [17]: "*Given the urgent need to decarbonise our electricity supply and enhance the UK's energy security and diversity of supply, the Government believes that new nuclear power stations need to be developed significantly earlier than the end of 2025*". This support is motivated by nuclear power's low life cycle carbon emissions and the reliability of modern plants: for example, the pressurised water reactor (PWR) at Sizewell B (in Suffolk) has an average availability factor[2] of 89% [19]. Although some of the older advanced gas-cooled reactors (AGRs) in the UK operate less reliably, the two reactor designs currently proposed for new build are both PWRs [20, 21] and are therefore expected to behave similarly to Sizewell B. All indications are that this pro-nuclear policy has survived the Fukushima incident as confirmed by the recent Weightman report on the safety and security of nuclear plants in the UK [22]. Nuclear power is one of the technologies that will benefit from a carbon "floor price" to be introduced from 2013, starting at around £16/tonne CO_2 [23]. Currently, up to 19 GW of new nuclear capacity has been proposed by various utilities and consortia; this compares to the current UK net operating capacity of around 10 GW [8].

As stated previously, at the present time electricity from natural gas and coal still dominate the UK electricity mix, providing 47% and 28% of electricity in 2010, respectively (see Figure 1). However, unlike coal, gas power is still expanding, particularly combined cycle gas turbines (CCGTs). Owing primarily to their low capital costs and the fact that they are a proven technology, CCGTs are likely to remain significant contributors to UK energy supply: since the beginning of 2009, the government has given planning consent to 13.5 GW of new CCGT capacity [24]. Moreover, there is evidence that some utilities are abandoning plans to build coal plants in favour of CCGTs for various reasons [see, for example, 25], as discussed below.

[2] Availability factor is the average proportion of time in which a plant is available to produce electricity [18] (referred to in [19] as 'operational factor').

Coal power meanwhile has been a major source of energy to the UK since the beginning of electrification. Its contribution has, however, declined greatly in the last two to three decades. When the UK electricity sector was privatised in 1990, coal produced 72% of electricity [26]. Following privatisation and the subsequent 'dash for gas', this figure declined rapidly and, in 2010, stood at 28% [5]. The contribution of coal will again decline markedly over the next few years as a result of the EU Large Combustion Plant Directive (LCPD): a total of 7.5 GW of coal plants have opted out of the LCPD and are therefore operating for limited hours and will permanently shut down by 31st December 2015 [27]. Additionally, the new Emissions Performance Standard limits emissions of new generators to 450 g CO_2/kWh at the point of generation [28], effectively banning construction of coal plants without carbon capture and storage. Nevertheless, the existing coal plants will still have a presence in the future UK electricity grid, and coal CCS is expected to provide a significant contribution [29]. The latter is supported by the government's plans to demonstrate power plants with CCS before 2020, including £1 billion of capital subsidy [30].

It is clear, therefore, that the coming years represent an opportunity to modernise and improve the UK's electricity supply, taking into account the economic, environmental and social impacts that may be accrued long into the future. This calls for a thorough and comprehensive sustainability assessment of the UK's electricity generation options, particularly those discussed above. However, there is currently no suitable framework for such an assessment. Development of such a framework has been the main aim of this project.

1.2 Project aims, objectives and novelty

This project has developed a novel framework capable of assessing the sustainability of electricity generation, taking into account techno-economic, environmental and social dimensions of sustainable development. The framework is generic and applicable to a range of electricity options and mixes. The specific objectives of the project have been:

- to review and critically examine existing sustainability assessment frameworks and indicators for electricity and related systems to inform the development of this framework;

- to develop a sustainability assessment framework and indicators applicable to different electricity options and mixes, taking a life cycle approach;
- to test the methodology and the indicator framework by carrying out sustainability assessment of different electricity options and scenarios for the UK; and
- to make policy recommendations based on the results of the sustainability assessment.

As far as the author is aware, this is the first example of such a study in the UK context. The main novelty of the research is in the following outputs:

- a methodology for assessing the life cycle sustainability of electricity generation technologies, focused on the UK but also applicable to other countries;
- the 42 sustainability indicators that form the core of the above methodology, developed via stakeholder engagement, original research and literature review (and published in Stamford and Azapagic 2011 [31];
- an analysis of the current electricity mix and potential future scenarios for the UK extending to 2070, together with a scenario analysis tool based on the findings of this research (attached on CD); and
- estimation of the future sustainability impacts of offshore wind, solar photovoltaics and coal with carbon capture and storage, including employment, worker injuries, costs and, in the case of photovoltaics, life cycle environmental impacts under UK conditions.

1.3 Dissertation structure

The dissertation is structured in the following way: the findings of the literature review are discussed in Chapter 2, while the developed sustainability assessment methodology and indicators are the subject of Chapter 3. Chapters 4 to 8 then describe the sustainability assessment and results for individual technologies. The sustainability assessment of different possible future electricity scenarios for the UK is discussed in Chapter 9. Finally, Chapter 10 provides conclusions and makes policy recommendations.

2 A review of existing frameworks and indicators for sustainability assessment of electricity

The sustainability of electricity generation has been the subject of numerous papers in recent years. Some of these have considered only environmental sustainability, while others have attempted to assess a broader range of issues, additionally covering economic and social implications. This review first considers frameworks and indicators for assessing the sustainability of electricity technologies and systems, discussing different environmental, economic and social indicators used in various studies. This is followed by frameworks used for some other industrial systems as well as indicators used at a national level. A full list of the indicators used by different studies can be found in Appendix 1. In total, 24 frameworks are examined in detail, set in the contexts of electricity generation and other systems including biofuel production, water mains provision and national sustainable development reporting. The findings of this review have been used to inform the development of the sustainability assessment framework in this project.

2.1 Sustainability frameworks for electricity generation systems

2.1.1 Techno-economic indicators

Technical and economic indicators are considered together in this section as they are often closely related. For instance, capacity factor describes the amount of electricity generated over a given time period relative to the maximum possible, and is therefore linked to cost: higher capacity factors mean more fuel must be purchased, but also that more electricity is produced relative to the initial investment in the power station.

Indicators to measure economic sustainability are readily available given that financial assessments have been carried out by businesses for centuries. However, in the field of sustainability, the number of economic indicators used generally remains small, with a core group of indicators that are widely used and a larger group of more specialised indicators (most of which are discussed later in this section).

One recent example of a simple set of techno-economic indicators is provided by Afgan and Carvalho [32] in their evaluation of a proposed hybrid energy system comprising solar photovoltaic (PV), biomass, natural gas combined cycle (NGCC) and wind turbine electricity generation technologies. Their analysis includes three economic measures: electricity cost per kWh, required investment cost per kW and overall thermal efficiency. This set of indicators is identical to that found in another of Afgan's papers, this time examining Bosnian energy scenarios [33]. Investment cost per unit power is a useful indicator as it allows direct comparison of systems across a scale of power generation capacities. However, it is also biased towards certain types of power, such as gas, for which construction cost is low relative to operational cost. For this reason, it may be preferable to include another indicator such as operational cost per kWh. In Afgan and Carvalho's paper though, the scope of their 'electricity cost' indicator is unclear: it is described as neither 'operational' nor 'life cycle' so it is not obvious whether stages like construction and decommissioning are included, or whether it is simply the cost of running the plant.

The same can be said of the 'average cost' indicator used both by Hirschberg et al. 2008 as part of the NEEDS project [34] and by Haldi and Pictet as part of the China Energy Technology Program (CETP) [35]. NEEDS was an international research project with the aim of evaluating the costs and benefits of current and future energy systems, while the CETP developed a framework for the future energy supply of Shandong Province based on gas, nuclear and coal technologies. In the latter, although the environmental assessment was conducted on a life cycle basis, it is not clear whether this also applied to the economic indicators. The units are described as '1999-yuan/kWh in 2020', which suggests the indicator is purely operational and does not include other life cycle stages such as construction and decommissioning. The authors also include total investment cost per unit power and 'fuel transport burden' (the percentage increase in fuel transportation required by each proposed scenario between 2000 and 2020). The purpose of the latter indicator is unclear, since increases in transport can have both positive and negative economic impacts (for example, increased fuel sales accompanied by increased infrastructure expenditure).

The economic indicators used by Kowalski et al. [36] in their assessment of renewable energy scenarios for Austria are mainly qualitative. They include 'effect on public spending' and 'regional economic development' in an attempt to estimate the indirect economic impacts of the scenarios under consideration. However, the assessment methodologies are not explained. The only indicator that is quantitative is 'costs', but again the scope and methodology for the quantification are not explained.

In contrast with the previous four studies, in their analysis of scenarios for the future of the Greek energy system, Diakoulaki and Karangelis [37] explicitly state that their electricity cost indicator encompasses initial investment (with a discount rate of 8%), depreciation, fuel, operation and maintenance. They also use total investment cost as a separate indicator, but it is not expressed per unit power and is thus arguably less informative. However, the same indicator is used by Hirschberg et al. 2008 in the NEEDS project to account for financial risk [34] on the basis that the absolute size of an investment is a risk factor due to the need to finance the investment and the possibility of power plant lifetime being cut short. Diakoulaki and Karangelis also assess the following technical factors: capacity factor (the percentage of full capacity at which the system runs on average), ability to respond to peak demand and security of supply. The latter two are certainly important: maintaining security of supply is seen as one of 'the greatest challenges facing the international community' [38], while knowledge of a system's response to peak demand is of vital importance to utility companies working within a complex, integrated energy mix. However, both of these indicators seem to have been simply assigned subjective values by the authors. While it is difficult to quantify these types of issues, an objective evaluation would have been more useful and transparent. The NEEDS project, for example, uses the total average variable cost ('dispatch cost') to describe ability to respond to peak demand [34].

Evans et al. [39] conduct an assessment of four renewable technologies: photovoltaics, wind, hydro and geothermal power. They use price, efficiency and 'availability and technology limitations' as indicators. The price of each system is based on average life cycle (cradle to grave) assessments derived from literature. However, the authors also display the range of cost estimates used, highlighting the extent to which non-combustion renewables are influenced by interest rates: since the majority of the cost involved is capital, the predicted interest rate causes great variance in the final life cycle cost estimate. 'Availability and technology limitations' is a qualitative indicator based on global capacity, availability, reliability and flexibility (i.e. ability to cater to both base load and peak electricity demand). These are important criteria from the utility company perspective and are also addressed by several other studies (such as NEEDS [34]). In contrast, electrical conversion efficiency is an attribute that is potentially of interest but is of little pragmatic merit, especially given the fuel-free nature of the technologies being considered. The redundancy of this indicator is particularly noteworthy since the final comparison of the technologies is achieved via a simple ranking analysis which places equal weight on each indicator.

A standard economic indicator of the cost of producing electricity is also included by Hirschberg et al. 2004 [40] ('production cost') in their assessment of electricity options in Germany. The indicator appears to encompass construction, operation and decommissioning. The authors also introduce another informative economic indicator: fuel price sensitivity. This is defined as the increase in production costs if fuel prices double, thereby providing a measure of the economic risk associated with each particular system given the unpredictable nature of long-term global economics and increasing fossil fuel scarcity. The same indicator is used in the NEEDS methodology by the same lead author [34] and by Roth et al. (also involving some of the same authors) [41]. This indicator is also applicable to fuel-free renewables (such as wind and PV) for which its value is zero, reflecting the benefit of independence from volatile fuel prices.

The paper by Roth et al. builds on previous work at the Paul Sherrer Institut (PSI) by carrying out an MCDA in collaboration with the Swiss utility Axpo Holding AG. The assessment is extremely extensive, involving 75 indicators and 18 technologies. However, in contrast to prior work involving PSI [34, 35, 40] there is no measure of electricity generation cost. Rather, Axpo used a net present value (NPV) model allowing estimation of profits as well as other impacts such as the effect on costs to consumers and cash flow to the state. This illustrates the potential usefulness of NPV, however it should be borne in mind that projections of revenue are needed to calculate NPV – including electricity sale prices and incentives available from government throughout the life of the project – which introduces additional uncertainty.

Hirschberg et al. 2004 [40] and Diakoulaki and Karangelis [37] use similar technological indicators, but the latter replaces capacity factor with availability factor (the average percentage of time during which the system is available to produce electricity). However, it appears that load factors (i.e. capacity factors) are being treated as synonymous with availability factors. The two are in fact distinct attributes and, if availability was the intended criterion, this situation penalises renewables due to the fact that they tend to have high availability but low capacity factors. Like Diakoulaki and Karangelis, Hirschberg et al. 2004 assess peak load response on what appears to be a subjective, relative scale. They also assess 'geo-political factors' on a similarly subjective basis. While these are important issues to take into account, the development of an objective quantification methodology for these indicators would improve transparency and robustness. The indicators 'long-term sustainability: energetic' and 'long-term sustainability: non-energetic' provide a measure of how long the earth's resources can provide for each type of technology without substantial increases in production cost. Energetic sustainability is based on the expected longevity of economically recoverable reserves at current extraction rates, although it is not stated how a value was assigned to nuclear energy given the huge dependence of long-term availability on fuel cycle choice.

Khan et al. [42] propose a sustainability indexing system referred to as LInX. It is based on life cycle thinking, and is applied by the authors to five power generation technologies including CCNG, biomass and three types of coal-fuelled generation. Economic indicators in LInX comprise initial cost (‘fixed cost’), operation and maintenance cost and health, safety and environmental costs. The latter accounts for the remediation of environmental damages caused by the system, but in the case of power stations it is not apparent whether this includes full decommissioning cost and waste disposal or simply average costs due to operation, such as accidental spills. The study also encompasses several technological considerations such as energy efficiency of production and ‘feasibility’ which is based on the classification of technologies as ‘new’, ‘relatively new’ and ‘old’ with old being favoured due to familiarity and perceived ease of implementation. While it is difficult to quantify the feasibility of a project, it could be argued that the age of the technology used is not an indicative parameter. For example, international uniformity of design of a power station could play a much greater role in feasibility than the age of the design. Despite this, other authors, such as Haldi and Pictet [35], have also proposed indicators whereby technologies are weighted according to their ‘maturity’. However, in the latter case the technologies are rated based on how close they are to feasible implementation rather than simply their age.

The ‘process conditions’ indicator suggested by Khan et al. penalises options that require extremes of temperature and pressure. However, extreme temperatures and pressures are not inherently undesirable: their disadvantages are manifested in higher construction costs and potentially higher operation and maintenance requirements, both of which should be accounted for by other indicators. Furthermore, high temperatures can be desirable in cases where process heat can be sold to nearby industrial plants. For these reasons, the utility of this indicator is questionable. Similarly, the ‘human-machine interaction’ indicator proposed by Khan et al. has little obvious usefulness: the authors define it as the percentage of time in which the system uses machines, with higher percentages being treated as favourable. In fact, while greater use of machines is potentially economically preferable as it could reduce operating costs, it also implies a reduced workforce, which is not favourable from a social sustainability perspective, meaning the indicators lacks a clear direction of preference.

Polatidis and Haralambopoulos [43] propose a ‘platform’ for integrated energy systems planning, and include a case study to demonstrate this platform. Their proposed indicators are used to assess Troizina wind farm, a planned 31.45 MW development in Greece. Their economic indicators include operational and installation costs per kW, net present value (NPV) and payback period. Both latter indicators are widely used to assess project feasibility, and as such are useful indicators in sustainable planning. They do, however, require assumptions about future revenue as well as costs. A further indicator, entrepreneurial risk, is expressed as a qualitative variable with an unclear methodology. Presumably it is based on subjective judgements. Finally, the ‘community economic indicator’ is a measure of the direct monetary contribution of the project to the local community. This is an element of socio-economics that is more thoroughly covered by the Global Reporting Initiative [44], which is discussed later.
Polatidis and Haralambopoulos also consider several technological aspects, including installed capacity, amount of imported oil avoided (with reference to an oil-powered electrical plant) and ‘reliability and safety’ (a qualitative scale based on factors such as peak load response and accident risk). The amount of imported oil avoided is presumably intended to shed light on the project’s contribution to security of supply: this is both an economic and a social consideration. It is a quantitative measure of the same impact area considered qualitatively by Diakoulaki and Karangelis [37] and in that respect is an improvement. However, oil-based electricity generation is now relatively rare in most of Europe, especially in the UK, so a local application of this indicator might be more relevant if it considered avoided imports of gas and/or coal since these are the predominant generation technologies.

The OECD’s Nuclear Energy Agency has produced a set of indicators for the assessment of electricity options [45] which shares several features with that developed by Hirschberg et al. [40], upon whose work it is partly based. As already mentioned, the most fundamental economic measure of sustainability is the cost of generation, and the NEA review the results of this indicator based on several different studies analysing generation costs in different countries. This highlights the great variation in results, mainly due to differing assumptions such as discount rate, operational life and capacity factor. However, the NEA’s own calculations of generation cost are given as ranges rather than discrete values in an attempt to account for this variation. Furthermore, they break down generation costs by investment, operation and fuel cost, highlighting detailed differences between generation technologies (such as the large investment cost components of nuclear power compared to either coal or gas, particularly when a high discount rate is applied). This detailed analysis and presentation allows the single indicator 'generation cost' to encompass construction cost, fuel cost and maintenance cost whilst simultaneously increasing transparency.

Other previously encountered economic indicators are also included, such as fuel price sensitivity and availability factor. Security of fuel supply is thoroughly discussed in terms of proven reserves of gas, coal, oil and uranium and their geographical distribution. However, no attempt is made to develop a methodology to apply a value to each generation system, which leaves the indicator essentially qualitative. Lifetime of fuel resources is based on global reserves and production in 2005, but unlike Hirschberg et al. [40], consideration is given to nuclear fuel cycle choices by providing lifetime figures following progressive introduction of fast breeder reactors, as well as the possibility of exploiting currently uneconomic uranium reserves. However, as is the case with security of supply, this added complexity prevents the establishment of a single comparable value for each generation system. Since the NEA's indicators serve more as points of discussion than data for MCDA, this is not problematic. The approach would, however, leave methodological questions unanswered if an MCDA was required.

Security of supply is not a factor considered by May and Brennan [46] in their appraisal of Australian energy options. However, since the options considered involve only coal and gas this is understandable, given Australia's considerable domestic reserves of both (at current production rates, reserves are expected to last approximately 180 years for coal and 58 years for gas [47]). Their economic indicators include capital cost, value added, capital inclusive value added and annualised cost. Here, annualised cost comprises all operating and maintenance costs plus annualised capital cost and therefore provides similar information to the NPV indicator used by Polatidis and Haralambopoulos [43], albeit it in an annualised form. The more complete economic assessment performed by May and Brennan is informative as it highlights the trade-offs between energy options. For example, brown coal (lignite) has higher investment costs but lower annualised costs than black coal, while combined cycle gas plants outcompete both of these systems on both counts.

The Global Reporting Initiative (GRI) proposes a very extensive indicator framework in its energy utility sector supplement for Corporate Social Responsibility (CSR) reporting [44]. Nine economic indicators are proposed, including 'direct economic value generated', which mirrors the value added indicator used by May and Brennan [46]. However, the remaining eight indicators are not easily applied to future projects (although several might feasibly be applied using industry averages). For example, the indicator 'financial implications of climate change' attempts to address the financial uncertainty resulting from the consequences of climate change, such as sea level rise or new regulations. Exact figures would be impossible to generate for this indicator, but considering these aspects could prove useful nonetheless. Likewise, the 'proportion of senior management hired from the local community', together with the 'proportion of spending on local suppliers', provides an effective measure of regional economic impacts. Both figures are, however, only truly useful at a company level where site-specific data are available. The same can be said of certain indicators used in Roth et al. [41] in which collaboration with a utility company allowed these kinds of criteria to be accounted for successfully. Examples include 'impacts on image of operator', 'education of employees' and 'compatibility with Axpo's corporate culture'. The authors do not elaborate on the quantification method for any of these indicators.

Financial assistance from government is also an indicator proposed by the GRI. Although it is categorised under 'economic performance', it might be used in a different light when viewed from a national perspective: since state funding for energy is essentially finite with different technologies competing for assistance, significant support for one technology constitutes lost opportunities for other technologies. The counterpoint to this indicator, 'cash flow to the state', is considered by Roth et al. [41]. However this requires knowledge of specific company finances and therefore cannot be applied at a generic technology level.

2.1.2 Environmental indicators

A wide variety of approaches to assessing the environmental sustainability of electricity is found in literature, ranging from a single indicator (such as emissions of carbon dioxide) to a number of different impacts including global warming, acidification, eutrophication and human health.

Only one environmental impact – carbon dioxide emissions – is considered by Afgan and Carvalho [32]in the concise indicator framework they apply to solar PV, biomass, natural gas and wind technologies. This is the most common environmental indicator used throughout literature, and is often seen as the most important due to the current prominence of global warming as a social and political decision-making criterion. However, CO_2 itself is not necessarily an accurate indicator of global warming since it fails to account for the contribution of other greenhouse gases (GHGs). Many of these other gases have a much higher radiative forcing capacity than CO_2 (for example, methane is 25 times more potent than CO_2 [48]). For this reason, it is more appropriate to assess the emissions of all relevant GHGs as 'CO_2-equivalents': an indicator of global warming potential (GWP). However, it should be noted that any value for GWP is only relevant over a specified time frame, normally 100 years, and this should be borne in mind when considering GWP figures, especially if they are to be compared across different studies. For example, over a 20 year time period, the GWP of methane is 72 rather than 25 [48], which could result in significantly different life cycle GHG emissions for any given system.

The same approach of considering only CO_2 emissions rather than total GWP is adopted by Diakoulaki and Karangelis [37] in their analysis of future energy systems for Greece. In addition to CO_2 emissions, the environmental indicators used include emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_x). (Afgan and Carvalho [32] also consider NO_x emissions, but as a social indicator. This is discussed in Section 2.1.3.) The contribution of both of these gases to acidification, human health and, in the case of NO_x, eutrophication, warrants their inclusion in the indicator framework. In this particular example, the inclusion of these indicators does not affect the overall environmental ranking of the four scenarios being considered, since CO_2, SO_2 and NO_x emissions are roughly correlated (this is because they are mainly associated with lignite-, natural gas- and oil-burning systems, the relative contributions of which vary only slightly between each scenario). However, the importance of including these two attributes is seen more clearly in Hirschberg et al. [40]: based on GHG emissions, they find oil and natural gas to be roughly comparable, with gas being approximately 8-20% better than oil[3]; but based on SO_2, natural gas is shown to be clearly preferable with emissions lower by approximately 85-95%[3]. While the above paper is discussed in more detail later, it serves here as a good illustration of the benefits of avoiding overly simplistic indicator sets.

In their assessment of Troizina wind farm, Polatidis and Haralambopoulos [43] quantify land use and CO_2 reduction potential (although it is unclear what alternative is being used to establish how much CO_2 will be avoided). They additionally measure the amount of new roads and electricity network necessitated by the wind farm as a proxy for landscape degradation and erosion. They do acknowledge, however, that new roads and networks have both positive and negative effects; moreover, these detriments and benefits are not confined to the environmental aspect of the development: new roads, for example, benefit local farmers socially and economically. Given the conflict of interests this indicator engenders, lacking as it does a clear direction of preference, it is arguable whether changes in its value can be interpreted in an informative way.

[3] Percentages calculated from authors' charts.

As in many sustainability assessments, Evans et al. [39] use life cycle GHG emissions as the main environmental indicator for their comparison of four renewable technologies. Water consumption and land use are additional attributes evaluated in the assessment. During their discussion of land use, the authors highlight an assumption which limits the reliability of land use estimates for renewable technologies: wind and PV installations often allow the continuation of existing activities on their allocated land area. In fact it is normal for these technologies to be installed, in the case of wind turbines, on farmland as a source of extra income, and in the case of PV panels, on the roofs of buildings. Neither of these cases results in any additional burden being placed on the environment due to the land occupied by the power system itself, since that land was already occupied. In the case of renewables, therefore, simply quantifying land use may not be reflective of any actual impact. Moreover, when reviewing the results of other authors, it is rarely clear whether they have considered dual-use land or have assumed that land is fully dedicated to wind or PV. This could be a source of bias against these two technologies.

In their assessment of electrical supply technologies in Germany, Hirschberg et al. [40] consider GWP, weight of waste produced, land use and change in unprotected ecosystem area (as a measure of regional environmental impacts caused by acidification and eutrophication). It should be noted that the authors avoid the problem discussed above by excluding rooftop PV installations from the calculation of land use. They do not discuss dual-use land in relation to wind, however. The impact category 'severe accidents' is quantified as fatalities/GWh. This is a useful measurement, although it does span environmental, economic and social dimensions and so might be better described as an integrated indicator. Similar indicators are considered in later work by some of the same authors: Roth et al. [41] consider all of the above with the addition of ecotoxicity and land contamination. However, the methods used quantify these impacts are not elaborated.

The environmental indicators included by the NEA [45] include global warming potential (GHG emissions), acidification potential (SO_2) and eutrophication potential (NO_x). Land use is also considered, highlighting the relatively high land conversion associated with wood, coal and oil electricity production chains. Non-radioactive and radioactive solid waste is quantified, along with emissions of particulate matter (PM_{10}). Although PM_{10} carries with it a significant risk of health problems such as lung disease it is often omitted from sustainability assessments. Its inclusion demonstrates the poor performance of lignite, coal and oil relative to natural gas, nuclear and renewables.

The main theme of the above indicators has been life cycle emissions, but resource use is also an important environmental impact category and is accounted for by some of the NEA's economic indicators: 'use of energy resources' gives the amount of fossil fuels required for each energy chain, while 'use of non-energetic resources' uses copper as a reference material to illustrate life cycle resource use for each system. The choice of copper as the sole reference material inevitably introduces bias into the assessment: in this case bias against photovoltaic systems (which require significantly more copper than the other technologies considered). This is the exact same method used by Hirschberg et al. [40] to assess non-energetic resource sustainability, where it carries the same bias. A more balanced option would be to include various non-energetic resources rather than relying upon one as a proxy.

To quantify resource use in their assessment of renewable energy scenarios for Austria, Kowalski et al. [36] measure cumulative energy input (GJ/TJ) and cumulative material input (kg/TJ). While the latter is less obviously biased than using copper as a reference material, it is still not a robust indicator. As no other explanation is given by the authors, it must be assumed that the mass of every material input is aggregated and subsequently averaged (per TJ output) over the life cycle of the system. If this is the case, no attention is paid to the scarcity or expense of individual materials. Therefore a system requiring, for example, 100 tonnes of concrete would not be differentiated from a system requiring 50 tonnes of concrete and 50 tonnes of copper, despite the latter having more of an impact in terms of resource use. Like the NEA, Kowalski and collaborators also measure emissions of particulate matter, SO_2 and GHGs. Stratospheric ozone potential is also considered, as are land use and eutrophication potential.

Further developments of environmental indicators are evident in the China Energy Technology Program (CETP) [35]. The authors consider energetic, but not non-energetic, resource use in terms of both absolute mass and as a percentage of known global reserves. This second measure provides useful extra information by putting life cycle resource use into a global context rather than simply presenting absolute figures. The authors' assessment of land use is also more complex than many papers which simply consider total area covered: in this case, the authors quantify the area of land degraded 'from one type to a lower environmental quality one' in km^2/GWh. However, the effectiveness of this indicator depends entirely upon the criteria used to determine the 'types' of land, and these criteria are not described.

In their evaluation of eight potential scenarios for the expansion of the electricity system in Bosnia and Herzegovina, Begic and Afgan [33] state that their resource use indicator measures the full life cycle requirements (in kg/kWh) of each scenario for fuel, carbon steel, stainless steel, copper, aluminium and insulation material. This provides a relatively broad appraisal of resource use, but by failing to consider each resource's known global reserves it gives an incomplete assessment of depletion: the potential functions provided by abiotic resources are ultimately constrained by their concentration in the Earth's crust, meaning an indicator of depletion should take this into account [49]. The indicator does, nevertheless, provide valuable information and allows a fairer comparison of different technologies than the copper-based indicator proposed by the NEA [45].

A far more complex appraisal of resource depletion is given by May and Brennan [46], who include four such indicators in their study of future Australian energy scenarios: the first is based on world depletion factors, the second on Australian depletion factors, the third is energy use per MWh, and the fourth is exergy loss per MWh (exergy, as defined by the authors, meaning 'useful energy'). These indicators build on previous work by the same authors [50]. Their use of Australian resource depletion factors is particularly interesting from a national perspective, as it highlights the large quantities of certain materials available domestically (such as coal), leading to a preference for energy chains that rely heavily on those materials.

Exergy loss, or use, has been proposed as an indicator of resource use in life cycle assessment by several authors in addition to May and Brennan [for example 51, 52] and, more broadly, as an indicator of ecosystem health [53]. It is based on the second law of thermodynamics: while energy is always conserved, exergy can be destroyed (the associated outcome being an increase in entropy); therefore, the most efficient use of resources is that which achieves a given amount of work with the smallest possible decrease in exergy (i.e. the smallest increase in entropy). In other words, our society can be regarded as an entity that consumes concentrated, highly ordered resources (resources of low entropy), such as metal ores, and increases their entropy by 'using' them. In this context, measuring our entropy production (that is, our consumption of exergy) illustrates how efficiently we use resources in general [54]. However, the exergy content of ores is generally low relative to the exergy content of fuels; therefore the life cycle exergy use of an energy system is likely to be dominated by the amount of fossil fuel used in combustion and transportation. Moreover, the chemical exergy content of any given fossil fuel is very similar to its calorific value (i.e. its energy content) [54], meaning little is gained by analysing exergy use instead of energy use. Additionally, in either case the scarcity of different materials is not accounted for, meaning resource use indicators involving depletion factors are arguably more informative.

The other environmental indicators used by May and Brennan [46, 50] are largely commonplace in life cycle assessments (LCAs): GHG emissions, acidification (SO_2-equivalent emissions) and solid waste production. They also assess PO_4-equivalent emissions as a measure of eutrophication and C_2H_4-equivalent emissions as an indicator of photochemical smog potential. The latter two impacts have not been widely evaluated in sustainability assessments, despite being amongst the most commonly considered impacts in environmental LCAs [55].

Further additions to the environmental indicators are found in Khan et al. [42] in their life cycle sustainability indexing system (LInX). Noteworthy indicators include ozone depletion (CFC-12-equivalent kg/kWh), oxidation potential (O_3-equivalent kg/kWh) and acidification [56], however acidification is measured in units of concentration of H^+ (or H_3O) ion as opposed to the usual approach of weighing emissions of relevant substances against their acidification potential factors. It is unclear how these H^+ measurements were made for each system under question. Pollutants released to air, water and land were quantified based on a ranking system developed by the National Fire Protection Association (NFPA) as opposed to the more common approaches of simply measuring volumes/masses produced or basing the values on tolerable daily intake (as suggested, for example, by [57]). However, Khan et al. propose an additional indicator, 'human health risk', which is based on cumulative hazard quotients and is therefore more similar to the tolerable daily intake approach. The origin of the hazard quotients, however, is not discussed. Hazard indices are also used by Khan et al. to quantify ecological risk: the indices themselves are constructed based on effluent quality criteria and air emissions standards, but again, their exact methodology is not conferred. Moreover, the relation of ecological risk to emissions standards may be helpful from a planning perspective, but is presumably country-specific and may not reflect the true environmental impact of the emissions. The authors also assess safety risk based on potential accidents and spills, but again, their methods are unclear. Finally, their resource depletion indicator divides resources into energy source, raw materials and renewable resources which are then aggregated into a single value. The inclusion of renewable resources (with examples given of wind and solar energy) is a peculiar addition to a resource depletion indicator since by definition they are not subject to depletion [58].

In the NEEDS project, Hirschberg et al. approach resource depletion by separating the problem into three indicators [34]. These measure consumption of fossil fuels (MW/kWh), uranium

(MJ/kWh) and metallic ores (kg SB eq./kWh). The metallic ore indicator is very thorough, considering consumption of 21 metal ores and normalising them to antimony based on their relative scarcities (following the approach typically used in LCA [59]). Other environmental indicators considered in the NEEDS project include: GWP; land contamination from accidental releases of hydrocarbons and nuclear accidents; chemical and radioactive wastes in need of underground storage; and three indicators which use the Eco-indicator 99 methodology [60] to address biodiversity loss, eco-toxicity, acidification and eutrophication. Eco-indicator 99 is a damage-oriented, endpoint LCIA approach that requires the adoption of one of three value systems: hierarchist, individualist or egalitarian. Additionally, the environmental impacts are expressed in terms of the potentially disappeared fraction of species and therefore require approximation of the number and type of species that will be affected as well as the total impact this will have on biodiversity. This introduces considerable uncertainty. As well as being highly complex, there is no consideration of the relative importance of individual species within an ecosystem. Roth et al. [41] appear to use the same indicators as the NEEDS project (the same authors were involved), presumably using the same Eco-indicator 99 methods, although this is not stated.

The GRI [44] proposes many environmental indicators for the energy utility sector. For example, in addition to material use, the percentage of recycled input materials is included to give a more realistic appraisal of resource use. While the framework lists several energy-related indicators (such as direct energy consumption), many of these are unsuitable for assessing future projects as they apply only to extant systems (such as 'energy saved through efficiency improvements'). Many of the indicators proposed, however, are applicable to project planning situations. For example, in addition to water use, a methodology is proposed to highlight water bodies that are significantly affected by normal operations: 'significantly affected' being defined as subject to annual withdrawals of more than 5% of their average volume. The percentage of water reused and/or recycled provides an additional measure of aquatic burdens. Discharges to water are also quantified both in volume and quality, assessing biological oxygen demand (BOD) and total suspended solids (TSS).

Several indicators introduced by the GRI are site or company specific and are therefore only applicable in certain cases. For example, the indicators proposed to assess biodiversity impacts include the number of IUCN Red List species in areas affected by operation. Similarly, expenditure on environmental protection (such as employee training and research and development) and the total number of significant spills are both site/company specific indicators.

More notable and generally applicable additions to the more commonly encountered environmental indicators include emissions of ozone layer-depleting substances (relative to CFC-11) and emissions (per MWh) of a wide range of air pollutants such as volatile organic compounds and particulate matter. Italian utility Enel, for instance, follows GRI guidelines in its annual sustainability reports; in 2010, it emitted 399.6 kg CFC-11-equivalent [61]. Belgian utility Electrabel, which also complies with GRI guidelines, reports emitting 3.2 mg/kWh of particulates in 2010 [62].

2.1.3 Social indicators

Social indicators of sustainability are generally considered underdeveloped relative to economic and environmental measures. While some studies considered in this review fail to include any true social indicators [such as 37, 56], others do begin to quantify the relevant issues. However, the social aspect of sustainability assessments has been the subject of widely varied approaches and the implementation of social indicators differs greatly in the literature. For example, in the approach developed by Afgan and Carvalho [32], the sole social indicator is NO_x emissions, which is normally considered an environmental attribute. Presumably this is an attempt to link the impacts of NO_x emissions to human respiratory and heart disorders (although this is not explicitly stated). Regardless, using only one social measure does not reflect adequately the importance of this dimension of sustainability. A previous paper by one of the same authors [33] includes another social indicator: employment provision (in hours/kWh). The same paper also refers to a 'diversity' indicator, but no units are given and it does not appear to be considered in the analysis.

A similarly sparse approach is adopted by Haldi and Pictet [35] in their assessment of energy scenarios in Shandong Province: employment is the only social aspect considered, this time based on combined salary (yuan/GWh) rather than time as in Afgan and Carvalho [32].

An extension of this is approach to social assessment is illustrated by Polatidis and Haralambopoulos [43] who include employment (in man-days per year) along with 'public acceptance' on a qualitative scale. While the latter indicator lacks clarification, the authors do point out that it is heavily influenced by factors like employment creation and local environmental impact. 'Public acceptance' is too general a concept to be assessed thoroughly on its own and therefore, in order to quantify it, must be divided into different measures representing its many facets. Three more innovative indicators proposed by the authors achieve this to some extent: noise creation (assessed as the decibel increase multiplied by the number of people affected), visual impact (a qualitative scale) and compatibility with other activities (a qualitative scale in which the authors attempt to establish the local importance of the land being used by the wind farm). Noise and visual impact are also considered by Hirschberg et al. 2004 [40] Hirschberg et al. 2008 (the NEEDS project) [34] and Roth et al. [41], again largely using qualitative scales.

This approach of dissecting the idea of public acceptance in order to quantify it better is mirrored in most other papers, although with varying levels of complexity. For instance, Khan et al. [42] use a simple, qualitative public acceptance indicator with four possible values ('accepted', 'neutral', 'reservations', 'unaccepted') alongside two other indicators described by the authors as 'socio-political': vulnerability of the area (which assesses the risk of natural disasters, extreme weather and riots) and 'social impacts' (a qualitative indicator based on expected local economic growth and infrastructure improvements). While an area's vulnerability is an important consideration from a planning perspective, the social impacts indicator is arguably too subjective and too complex to capture in a single indicator.

Similarly, Evans et al. [39] use a qualitative indicator to address social issues, although the impacts considered are quite comprehensive. Toxin release, noise, bird strike risk and visual amenity all feature as criteria, as do river damage, displacement of animals and people, effect on agriculture, effect on seismic activity and odour. While this represents a broad spectrum of impacts, it does not include employment or human health. Furthermore, several of the impacts considered (such as noise) could potentially be quantified, which would increase reliability.

The same can be said of the social impacts assessed by Kowalski et al. [36]. All their social indicators are qualitative, with the exception of employment, which is measured as the number of jobs provided for each scenario. However, this is given as an absolute number of employees required (in contrast to the worker hour requirements measured in most other studies [such as 43]). The authors' qualitative social indicators include issues such as social cohesion, noise, smell, social justice and empowerment, but no information is given about how their results were derived.

Further developments of social criteria are found in Hirschberg et al. 2004 and 2008 [34, 40] which again include a measure of employment (this time in person-years per GWh) but, in an attempt to further quantify public acceptance, also include the 'maximum credible number of fatalities per accident' as a proxy for risk aversion (where 'credible' represents an upper estimate of fatalities for each technology, based on historical events). The former study also measures the necessary confinement time for waste, which is most significant for nuclear energy. It could, however, be a useful indicator with which to differentiate between different nuclear fuel cycles as well as carbon capture and storage technologies (which are not considered in [40]). Human health impacts from normal operation are measured as years of life lost (YOLL) per GWh, while the NEEDS project also adds disability-adjusted life years (DALYs) to take account of non-fatal illness (DALYs are discussed further in Section 3.2.3.2). In Roth et al., a greater number of such indicators is included, additionally covering the potential impacts of terrorism in terms of fatalities, lost production and cost, as well as mortality and morbidity. Given the involvement of the same authors, it is likely that the latter two indicators are based on DALYs, but this is not stated.

As mentioned previously, the three studies above measure local disturbance due to noise and aesthetics on a subjective, relative scale. While it would be preferable to objectively quantify every possible indicator, it is probably not feasible with an issue as subjective as aesthetics. Noise, however, can be quantified objectively, as was demonstrated by the indicators of Polatidis and Haralambopoulos [43] discussed earlier. Finally, Hirschberg et al. adopt a binary indicator with which to measure nuclear proliferation risk (0 meaning 'no risk', 1 meaning 'risk'). Clearly this is a very simple indicator for a technically complex issue, but assessing proliferation risk in a concise manner is extremely difficult. The NEEDS project report by the same lead author similarly uses an ordinal scale based on expert judgment. Indeed, NEEDS uses a suite of ordinal scale-based indicators in the social impact category, covering issues from the diversity of fuel suppliers to the average years of education experienced by the work force (full list in Appendix 1). Roth et al. [41] include many similar indicators based on expert judgment addressing issues such as the potential for social conflict and trust in the plant owner (again, see Appendix 1). Many of these indicators can provide a more nuanced understanding of the social impacts of electricity generation than the more direct impacts traditionally assessed. However, they also necessarily decrease transparency as well as introducing factors into the analysis that may be subjective or values-based (for instance, the quantification of 'fair distribution of risks and benefits' in Roth et al. raises the question, 'who decides what is fair and what is not?').

The NEA [45] proposes only five social indicators, all of which have previously found use in sustainability assessments: employment; health effects from normal operation (YOLL/GWh); necessary confinement time for hazardous waste; proliferation risk and risk aversion. These indicators and their methodologies were used by Hirschberg et al. [40] in their appraisal of energy systems in Germany (a paper on which much of the NEA's work is based). Like that paper's authors, the NEA do not propose a method by which proliferation risk could be quantified.

Since May and Brennan [46] do not include nuclear power in their scenarios, they do not consider proliferation risk or hazardous waste confinement. They do, however, measure worker safety: lost-time injuries and worker fatalities are collated for all the stages of the system life cycle. The authors acknowledge that this does not account for near misses, minor injuries and illnesses that occur later in life. In measuring employment though, the authors propose a more complex approach: indirect employment is taken into account in addition to those jobs directly created by each scenario. This allows the inclusion of jobs created for temporary staff and as a result of direct employees' spending, for example. This inclusion of the effects of increased disposable income on overall employment levels (typically referred to as 'induced' employment) can provide a more informative picture of the true employment impact. However, it creates significant uncertainty as it must be estimated using a multiplier so that, for example, 0.25 induced jobs are assumed to result from every one direct or indirect job [as in 63].

The GRI introduce a large number of social indicators based on four categories: human rights, labour, product responsibility and society. Of these, most are company-specific, for example 'total hours of employee training on policies and procedures concerning aspects of human rights' and 'total number of incidents of discrimination and actions taken'. However, some may be of relevance when based on industry averages, for example the total number of indigenous peoples' rights violations is an issue relevant to uranium and coal mining. (It may be noted that Azapagic [64] suggests a similar indicator to either complement or substitute the GRI's: 'percentage of quarries/mines on sites sacred for indigenous people relative to the total number of quarries/mines'). Employee turnover provides a measure of employee satisfaction, while the composition of the total work force throughout the supply chain might be of interest regarding equal opportunities. Under the section 'product responsibility', the GRI introduces some indicators that provide a social measure of the reliability of an electrical system: power outage frequency and duration, measured using the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) respectively. Similar measures have been proposed by other papers such as Sahely et al. [56], but are generally considered simply as technical or economic indicators. Since SAIFI and SAIDI measure service interruptions per customer, they introduce a tangible social dimension to reliability. However, they are of more relevance to the operators of the electricity grid than to owners of individual plants, making them of limited use in comparing different technologies.

2.2 Sustainability indicators for systems other than electricity generation

This section reviews frameworks and indicators used in the assessment of technologies and systems other than electricity production. The systems considered by studies included in this section are bioethanol production, energy crops, water mains systems, mining and generic industrial activity. As discussed below, assessment frameworks addressing these systems often include indicators relevant to the electricity sector due to their broad similarity: for instance, costs, safety, emissions to air, land and water and the resulting environmental and health impacts are all important considerations in each case.

2.2.1 Techno-economic indicators

Sahely et al. [56] provide an assessment of Toronto's urban water system as part of a larger paper on sustainability indicators for urban infrastructure systems; the Toronto case study is conducted partly in order to demonstrate their proposed indicators. Sahely et al. use the indicators solely as a basis for critique rather than a means of conducting a more formal analysis, such as an MCDA. Quantitative information is, however, provided for all the indicators. The sole economic indicator used in their water system case study is a measure of investment and operational costs, expressed both in absolute terms and as a percentage of the GDP of Toronto. While this might provide an interesting comparison across administrative regions, it is only applicable to state-funded exercises, and is therefore not relevant to UK electricity supply projects. The authors also suggest several indicators which they do not use in their case study, including cost per household, expenditure on research and development and reserve funds, but these cannot be easily applied to comparative assessment of technological options.

Energy production techniques from grassland in Germany are examined by Rösch et al. [65] using a framework of 16 indicators. The framework is applied to various forms of biogas production and the combustion of hay and wood. It is therefore relevant to the electricity sector as it shares common features such as transportation and combustion of fuel. The assessment also uses a fully integrated approach (i.e. there is no explicit distinction between environmental, economic and social indicators). The authors propose only two economic indicators, the first of which is the 'cost of avoiding CO_2 emissions' via the authors' biomass energy production scenarios (measured in €/t CO_2 avoided). The results of this indicator highlight the high cost of using these techniques to reduce carbon emissions relative to the cost of EU carbon emission certificates. The second indicator is 'wage compensation' (€/working hour), which is a measure of each scenario's contribution to the farmer's income. This is a much more relevant indicator in the selection of a farmland biomass energy scheme, although it might also have been of pragmatic interest to include capital costs, as high up-front costs may be a decisive factor. Following the evaluation of the indicators, the scenarios are simply ranked from 'best' to 'worst'. The authors cite the preservation of transparency and a reluctance to make assumptions as reasons to avoid further analysis, such as an MCDA. However, an extension to this work involving stakeholder input to elicit preferences and ease the process of selecting a preferred scenario would prove beneficial.

An analysis by Smeets et al. [66] of the sustainability of bioethanol production in São Paulo, Brazil, is considered in this review because some of the indicators could be applicable to biomass-based renewables. While many of the papers discussed here use indicators as part of an MCDA, Smeets et al. use them only as a basis for discussion and review: although much of the information is quantified, no mathematical appraisal is conducted, and the authors acknowledge that 'the analysis in this article is based on a subjective assessment'. As part of their analytic hierarchy process, the authors include 'economic effects on the local community', 'capability of proper operation and maintenance during the life cycle' and 'social costs'. However, these are all valued qualitatively and the scope of the social cost indicator is not clear. The indicators proposed as part of their real cost estimation include construction costs as well as maintenance, security and environmental remediation costs but these final three are not valued by the authors due to 'the inadequacy of available cost data'. In the case examined by the authors (water mains replacements), these costs may be of little interest as they are assumed to vary little from one option to the next. However, in decision making in other sectors, such as energy, maintenance and environmental costs may vary hugely and therefore be vitally important.

This is reflected in the indicators suggested by Azapagic and Perdan [57] in their general framework for industry by the inclusion of expenditure on environmental protection per functional unit (functional unit being defined as the unit of assessment, such as kWh of energy or kg of product). They also propose several indicators that are best suited to corporate reporting, such as staff turnover, ethical investments per functional unit and contribution to GDP. However, they also advocate an adaptation of this indicator for the assessment of single products by valuing the contribution of its production to the average GDP of every country involved in the life cycle. While this could become extremely complicated to calculate, it would provide extremely valuable information from an international sustainability perspective.

The indicator framework proposed for use by extant mining companies by Azapagic [64] is based on the GRI and is also therefore focused on corporate reporting. However, many indicators (too many to mention here) are relevant specifically for the mining stage in the life cycle of energy systems, particularly those requiring fuel mining (such as coal and nuclear power). Some of the indicators are both novel and exploitable throughout the whole life cycle of an electricity generation system, such as the total costs of employment as a percentage of net sales. This indicates the contribution of human capital to income and might be supplementary to social indicators addressing the amount of employment generated.

2.2.2 Environmental indicators

A range of environmental indicators is used by Smeets et al. [66] in their analysis of the sustainability of bioethanol production in Brazil. For example, as well as discussing GHG emissions rather than solely CO_2, they introduce parameters such as water use. Water use is significant for many industrial processes, and is doubly significant for bioethanol production due to its use both in crop irrigation and in the industrial production of ethanol from those crops. The use of this indicator allows the authors to identify a potential future problem in bioethanol production: while the industry's current water use is a small percentage of the area's total water supply, irrigation is rapidly gaining popularity in West São Paulo, which could elevate total water use to unsustainable levels if the trend continues.

Along with water use, water pollution is also considered, encompassing both organic pollutants and agro-chemicals such as pesticides. This is an especially pertinent indicator given São Paulo's severe water pollution problems in areas like the Piracicaba river basin. Biodiversity impacts are also included in the assessment, although a lack of data forces the authors to use land conversion as a proxy, disregarding any indirect impacts bioethanol production might have on biodiversity. Soil erosion is also considered, with the rate of erosion (t/ha/yr) used as its indicator. Fertiliser application rate (t/ha/yr) represents the impact on nutrient leaching, while sugar cane burning (percentage of the harvested area) is an indicator that explores multiple impact areas such as GWP, human health and energy efficiency. The final environmental indicator proposed by Smeets et al. is the use of genetically modified organisms (GMOs). Citing a lack of criteria and 'negative attitudes towards GMOs in the EU and Brazil', the authors propose an outright rejection of the use of GM sugar cane in any scenarios. They do, however, recognise the possibility of assessing GM cultivars if suitable criteria become available. The development of this indicator would certainly provide valuable information, and could perhaps include sub-indicators such as the risk of cross breeding with wild species.

In their sustainability assessment of energy from biomass and biogas produced on German grassland, Rösch et al. [65] include standard environmental indicators such as GHG emissions, eutrophication potential and acidification potential. In order to measure human health impacts, the authors measure summer smog potential and emission of particulate matter, CO, NO_x and fungal spores (resulting from the storage of wood chips). Savings in fossil fuel use are quantified as a measure of the substitution of non-renewable resources, however this is the only indicator in the study to touch upon resource depletion: non-fossil fuel resources (such as construction materials for biogas generators) are not considered. Three qualitative indicators complete the framework by considering effects on biodiversity, soil and groundwater.

A similar number and type of sustainability indicators is presented by Sahely et al. [56] in their assessment of Toronto's urban water system. The first impact category considered is resource use, starting with energy use. Sahely et al. use this term specifically to mean electrical energy (which is potentially misleading, as a large proportion of the energy used by an industrial process is likely to be non-electrical, such as process heat, heating of buildings and the transportation of supplies, products and staff.). The authors also use this indicator to evaluate qualitatively energy efficiency, pointing out that biogas from municipal waste water sludge has the potential to produce electrical energy and, more specifically, 9.3 times the amount of electricity needed to process it. The processing of waste water can thus be a net producer of electricity, an option increasingly being exploited by water treatment companies. Chemical use is also considered, with the chemicals in question being those used most commonly in the treatment of water and waste water, such as chlorine, ammonia and SO_2. Nutrient leaching and 'sludge' are proposed as additional indicators, although since these are not used in the authors' assessment of Toronto's water system, the methodology of their implementation is unclear.

The final environmental impact category considered by Sahely et al. is 'residuals': GHG emissions and discharges to water. The former indicator includes direct emissions of GHGs (those generated on site) as well as indirect emissions (those generated off site, in this case during production and transportation of fuels and electricity). 'Discharges to water' includes three sub-indicators which can quantify the quality of those discharges: biological oxygen demand (BOD), total suspended solids (TSS) and total phosphorus (TP). Disposal of 'sludge' to landfill is a measure of the extent to which solid waste is incinerated, landfilled or recycled (for instance by application to agricultural land). The treatment of solid waste is an important back-end process that can have significant impacts on the environment, and from this perspective landfilling is one of the least desirable options. However, incineration is seen as the most costly and potentially the most polluting due to combustion gases [67]. For this reason, disposal of sludge by incineration may have been a more informative indicator. In either case, it is not readily applicable to the electricity sector.

Like Sahely et al., Koo and Ariaratnam [68] have presented a sustainability assessment and decision-making framework for water mains systems, in this case applying a case study to Scottsdale, Arizona. Their assessment framework is extremely complex, comprising several separate analyses: an analytic hierarchy process with 29 qualitative indicators; a real cost estimate using eight quantitative indicators; an energy and pollution estimate for only the construction phase with 18 quantitative indicators; a time estimate with five quantitative indicators; and a resource depletion analysis using eight quantitative indicators. A final value is calculated for each of these analyses and individual weighting is applied to each one before bringing them together in an MCDA. While the methodology appears to be comprehensive, the extent to which life cycle thinking is applied is obscured by the piecemeal nature of the analysis. For example, the real cost estimation is a cradle-to-grave analysis, while the energy and pollution estimates only apply to the construction period and production of materials, disregarding other stages such as maintenance and decommissioning. Moreover, in the final MCDA, the greatest weighting (35%) is applied to the analytic hierarchy process (AHP) which contains only qualitative indicators.

Despite these complications, several relevant indicators can be elicited from the study. For instance, the quantitative pollution estimates are similar to those used in some simpler sustainability assessments: CO_2, SO_2 and NO_x emissions. As in previously mentioned papers [32, 37] the CO_2 indicator does not provide a true reflection of global warming potential because no other GHGs are considered. However, the qualitative indicators included in the authors' AHP assessment are broader in scope: for example, the recyclability of scrapped metal and long-term water, air and soil pollution are measured, although how they are assessed is not clarified. The number of endangered and threatened species on site is another significant consideration for any large-scale construction project. The paper also describes several useful, quantitative energy use indicators such as daily fossil fuel use during construction and embodied energy of construction, which measures the total energy used from raw material extraction to assembly on site. The authors also assess resource depletion in a compound indicator which takes account of the major materials used, their global availability and the mass used. This indicator results in a final 'rate of depletion' measure calculated as *mass* × (*1 ÷ global availability (years))*. This constitutes a simplified yet informative version of resource depletion indicators used by other studies such as May and Brennan [46].

The same resource depletion indicator is proposed by Azapagic and Perdan in their general indicator framework for industry [57] but with the inclusion of biotic, as well as abiotic, resource use (such as the 'use' of endangered species). On face value this has no application in the energy sector, but might be adapted to assess biotic impacts such as bird deaths caused by wind farms (an issue which is of interest to ecologists and the public alike, especially considering the UK's offshore wind resources and large seabird concentrations [69]). Other standard LCA indicators included by the authors are GWP, ozone layer depletion, acidification, eutrophication and photochemical smog. Human toxicity potential and eco-toxicity are also assessed via tolerable daily intakes and maximum tolerable concentrations of various chemicals. Overall, the environmental element of this indicator framework is quite comprehensive, including most previously mentioned indicators such as solid waste production, total energy use and material recyclability. A number of new indicators are added to this list, including product durability and the qualitative indicator, 'service intensity' (the extent to which a service is provided without further resource use, for example via leasing as opposed to selling). However, these are not applicable to the electricity sector, as electricity is neither durable nor leasable.

Azapagic [64] significantly augments and adapts the indicators proposed by the GRI (discussed in section 2.1) to provide an indicator framework consisting of over 130 individual attributes of which 60 are environmental. While these are aimed specifically at the mining industry and are too great in number to mention in detail, there are many notable environmental indicators that are relevant to the energy industry as a whole. For example, land use indicators are developed further by introducing land type rather than simply land area ('converted ancient or rain forest land area' is a standalone indicator in addition to total land use). This is a similar indicator to that of Haldi and Pictet [35] who quantify the area degraded from one land type to another, but here the methodology is clearer. Land contamination is considered by calculating the percentage of occupied land that has been contaminated by operations, while use of renewable energy is evaluated as a percentage of total energy use.

2.2.3 Social indicators

Panthi and Bhattarai [70] apply 26 indicators to an assessment of the sustainability of community-based water projects in Nepal. These indicators cover technical, financial, institutional and 'social/environmental' impacts, but they are all assessed qualitatively. Since the authors conduct their assessment partly as a demonstration of multi-criteria decision analysis (MCDA), they require numerical outputs for each indicator, and therefore use a percentage score system based on a 'five point grading nomenclature' of poor, fair, good, very good or excellent. These grades are assigned following interviews, group discussions and field assessments. However, qualitative indicators, no matter how rigorous, are still open to subjective assessment and should therefore be used secondarily to quantitative indicators as far as is feasible. Nevertheless, some of the indicators assess important social factors such as community participation (in decision making and in operation and maintenance), racial and sexual equality and water supply reliability. It should be highlighted though, that the Global Reporting Initiative [44] provides ways by which some of these issues might be measured objectively: for instance, community participation might be assessed by the percentage of employees hired from the local community.

The social issues compiled by Koo and Ariaratnam [68] represent some of the key areas of concern for large infrastructure projects, such as public and worker safety, public acceptance, social and cultural impact, resident relocation, vulnerability to sabotage and construction 'nuisances' (from noise, vibrations and visual impacts). However, like the indicators presented by Panthi and Bhattarai [70], these are all assessed in a qualitative manner and are therefore open to subjective interpretation. Furthermore, the methodology used to value the indicators (such a key criteria upon which the values were based) is not declared. None of the authors' quantitative indicators (which include, for instance, diesel consumption and CO_2 emissions) address social issues.

In contrast, Rösch et al. [65] quantify the social impacts of their scenarios for biogas and biomass production from grassland, if only to a certain extent. Two social indicators are presented, of which one, employment, is quantitative, being measured as the working time required per hectare for each scenario. The second indicator is a qualitative appraisal of the effect of the energy technologies on the local landscape. Although two indicators are not sufficient to measure the full range of a system's effects on society, the assessment of a measurable social impact is highly valuable from a local viewpoint. On the other hand, many social issues that were examined qualitatively by Koo and Ariaratnam [68] are neglected here.

A greater range of quantifiable social indicators is provided by Smeets et al. [66]. Since the authors are examining bioethanol production, their indicators are more specific to agriculture than to electricity production. However, they do cover some of the same issues, such as employment. In this case though, employment is further divided: 'direct' employment refers to on-site job opportunities; 'indirect' employment is that which appears in other areas of the supply chain; and 'induced' employment is the change in employment generated by the project (e.g. the increase in retail job opportunities due to augmented disposable income of employees). These three categories of employment provide a more realistic appraisal than simply counting on-site job opportunities. Nevertheless, they introduce quantities that are difficult to measure and may be accompanied by significant uncertainty and error. Smeets et al. take the measurement of employment-related effects further by, for example, using the Gini coefficient[4] to assess income distribution. The authors use this measurement to compare the income distribution of the bioethanol/sugarcane industry to the national average in order to elucidate the effect of the industry on the gap between rich and poor. The authors also include a 'wages' indicator in which the industry-average wage is compared to the national average and national minimum. Working conditions are established by quantifying worker injury rates and the percentage of payroll spent on benefits such as pensions, health care and education. Indicators like these help to provide a real measure of the social consequences of the system under question. They do, however, rely largely on industry averages and thus do not account variation between different regions and companies.

A greater range of social matters is addressed by Azapagic and Perdan [57], although eight of the 11 indicators proposed are qualitative. The range of issues considered by these indicators includes stakeholder inclusion, involvement in community projects, improper business dealings and intergenerational equity. This final indicator is of particular importance to the energy sector, since most projects initiated in the near future have long lifetimes and will affect several future generations. Despite its importance, it is an issue very rarely considered in sustainability assessments due to difficulties in its quantification. It is assessed here by considering the creation of problems with no present-day solution, albeit it on a qualitative basis. Like Smeets et al. [66],

[4] The Gini coefficient is a measure of a sample's deviation from perfect equality (i.e. the difference between reality and a situation where everyone has the same income). A higher Gini coefficient therefore represents less even income distribution.

Azapagic and Perdan introduce an income distribution indicator, but in this case it is the income of the top 10% of employees as a fraction of the income of the bottom 10%. While this is a simpler calculation than the Gini coefficient, the difference between the results of the two methods is not clear since they have not been compared. Work satisfaction is another social consideration that is difficult to quantify, and here the number of sick days per functional unit is used as a proxy. While this inevitably overlaps with worker health impacts, no other methods (aside from carrying out worker surveys) have been proposed.

The social indicators proposed in a later paper by Azapagic [64] are only applicable to the mining stage of the life cycle, but many of them are novel. For example, the percentage of sites with 'fly-in, fly-out' operations relative to the total number of sites provides a powerful measure of the benefit of mining to local communities, gauging both local economic benefit and local acceptance, which in turn influences public acceptance as a whole. Another similarly informative indicator is the number of proposed developments that require resettlement of communities. These indicators are, however, quite company specific, making them less suited to a generic comparison of alternatives.

2.3 National-level sustainable development indicators

Since the publication of 'Our Common Future' by the UN World Commission on Environment and Development [1], commonly referred to as the Brundtland Report, many attempts have been made to develop sustainable development indicator frameworks for national use. This process was made more concrete after the adoption in 1992 of the UN's 'Agenda 21' [71] by 178 governments, which explicitly stated that 'countries at the national level… should develop the concept of indicators of sustainable development in order to identify such indicators'. Many of these frameworks of national-level indicators are now well established and comprehensive. Examples are found in Australia [72, 73], Canada [74], France [75], Germany [76] and the UK [77]. The UN also provides a set of indicators for national or regional use [78]. However, such frameworks are intended to chart the progress of an entire country towards sustainable ideals, and as such have limited use in assessing the sustainability of individual projects or technologies. Despite this, they do provide a basis from which appropriate indicators might be adapted. For this reason, two of the most apposite frameworks are considered: the UN's Indicators of Sustainable Development [78] and the national indicator set of the UK Sustainable Development

Unit [77]. These two were chosen due to the former's comprehensive coverage and the latter's specificity to the UK, upon which this study is focused.

2.3.1 Economic indicators

The UK Sustainable Development Unit (SDU) [77] considers 68 indicators grouped into 15 varied categories. Aside from expressing several environmental measurements relative to GDP (such as water resource use; see next section), the UK SDU [77] presents few economic indicators. Those that are used are not easily applied beyond a national context: for example, GDP and GDP per head are analysed and compared to the equivalent values for other G7 countries. Total government investment relative to GDP is charted over several years, but the values are based on an index, the origin of which is not explained. This replacement of absolute data with an unexplained index serves only to decrease transparency. In contrast, net Official Development Assistance (ODA) to developing countries is given as a percentage of gross national income and compared to other G7 countries.

Net ODA is also included by the UN [78] in its set of 96 indicators for sustainable development (of which 50 form the 'core' set), attesting to widespread similarities between the two indicator frameworks. The UN also suggests familiar national-level indicators such as GDP per capita and inflation rate. Economic loss due to natural disasters (as a percentage of GDP) is a proposition that could potentially be considered at a project level as a measure of vulnerability to environmental stochasticity, but a different assessment method would have to be developed. Similarly, the framework includes 'expenditure on research and development as a percentage of GDP': a measure that could certainly be informative on a company level if it was expressed differently (perhaps as a percentage of total expenditure).

2.3.2 Environmental indicators

The UK SDU framework includes universally applicable indicators such as GHG emissions, percentage of electricity supplied by renewables, emissions of CO_2, SO_2, NO_x and PM_{10}, total material consumption and water use. Certain indicators, although primarily of use at a national level, might be applied to specific sites for development of new energy projects: for example, a water stress indicator categorises geographical areas of the UK based on the Catchment Abstraction Management Strategy of the Environment Agency. This could provide important information when considering different sites for water intensive energy technologies. Similarly, 33 ‘priority habitats’ and 288 ‘priority species’ are considered, which address site-specific concerns. Other notable indicators include ‘land recycling’ which quantifies the percentage of new developments on previously developed land. In a project planning scenario, this indicator could provide valuable additional information to the more commonly used indicator of total land use.

As the sustainable development indicators proposed by the UN are intended for national use [78], many of them are similar to those proposed by the UK SDU. For instance, the ‘atmosphere’ category comprises assessment of ambient air concentrations of pollutants such as ozone, PM_{10}, SO_2, NO_x and volatile organic compounds, as well as emissions of GHGs and ozone layer depleting substances. The former ambient air measurements are aggregated into a single indicator, ‘ambient concentration of air pollutants’. While an ambient level of a pollutant is not an appropriate criterion in evaluating different electricity options, the expected life cycle emissions of that pollutant are.

Impacts on land use are analysed by the UN indicator set using two indicators: land use change and land degradation. The former is intended to monitor land use in a country over time, based on categories such as arable land, woodland, permanent pasture and built-up areas. The equivalent indicator in an energy planning context would be land use change resulting from the system life cycle. The second land use indicator is similar to that proposed by Haldi and Pictet [35] in that it quantifies degradation. The problem this presents is one of transparency and consistency: the UN’s guidelines describe degraded land as that which is, ‘affected by soil erosion, deterioration of the physical, chemical and biological or economic properties of soil and/or long-term loss of natural vegetation’. No strict rules are applied by which these criteria might be met, which leaves the indicator open to quite wide interpretation.

Another notable environmental indicator proposed by the UN is ‘fragmentation of habitat’. In its original context, this indicator assesses the patch size distribution of different habitat types, such as forest, in an attempt to account for the detrimental impacts of habitat area loss and increase in ‘edge habitat’ that accompanies fragmentation. In an assessment of future scenarios, the life cycle effects of the system on habitat fragmentation could be quantified by the change in patch size distribution. Other relevant indicators, such as biological oxygen demand of water and wastewater treatment, have been used by other studies in a form more readily applicable to scenario assessments [see 44, 56].

2.3.3 Social indicators

The social aspects of sustainable development measured by the UK SDU [77] are varied and culminate in a composite indicator referred to as 'wellbeing'. However, as is the case with the majority of national-level indicators, few can be used to inform electricity system analysis. For instance, fear of crime may be a useful indicator when considering national policies, but is of little relevance to the electricity sector. Equally, suicide rates and 'healthy life expectancy' are quantitative measures providing some indication of wellbeing but are most useful at a national level. As is reflected by the SDU indicators, wellbeing is such a multifactorial attribute that its quantification can rarely be thorough without resorting to detailed surveys and questionnaires. It is for this reason that several 'self-reported' measures are taken, such as general health, perceptions of anti-social behaviour and overall satisfaction with various aspects of life (such as leisure, community and standard of living). While this approach is doubtless the most comprehensive method of collecting data about many aspects of social development, the results are very sensitive to the form of the questions asked and to other situational factors [79]. Moreover, some evidence suggests that responses to questions about happiness or wellbeing are derived less from external, alterable factors than from genetics and personality [80], making them of limited use in a decision-making context. This is, however, a contentious topic [see, for example, 81, 82].

Other indicators used by the UK SDU include national employment (measured as the percentage of working-age people in employment) and pensions provision (the percentage of people contributing to a non-state pension). These indicators address ideas that are of relevance in an energy planning context and could be adapted to that end by, for example, measuring working hours per kWh and quantifying the percentage of the total supply chain workforce participating in a company pension scheme. A final indicator of interest concerns social justice and inequality, but at the time of writing it is still being developed.

The UN indicator framework [78] covers much of the same ground as that of the UK SDU. Typical national-level indicators include healthy life expectancy, proportion of the population living below the national poverty line and suicide rate. More relevant indicators include income inequality, assessed as the ratio of share in national income of the highest to lowest quintile. This is similar to previously encountered indicators of income distribution [see 57, 66]. The theme of inequality is also extended to gender bias by assessing the share of women in employment in the non-agricultural sector, although this is clearly not an applicable measurement for energy systems.

Previously discussed frameworks, such as that by the GRI [44], have included assessment of employee training since higher training suggests efficiency and better implementation of company-wide social and environmental policies. The UN, too, proposes its assessment by suggesting the percentage of the population aged 25 to 64 in education or training as an indicator. In the description of this indicator, continued learning is cited as 'essential to sustainable development'. A final UN indicator that may be of relevance to social assessment for energy systems is 'share of imports from developing countries and LDCs (least developed countries)'. As is highlighted by the indicator description, 'exports from developing countries… constitute a major source of external financing for sustainable development of those countries'. This represents a similar mode of thought to that exemplified by local economic impact indicators, such as the proportion of spending on local suppliers [44]. Applying this in an energy context could be both informative and novel, provided representative information was available. However, in practice, the choice of suppliers is a company policy issue rather than one applicable to generic technology assessments.

2.4 Summary and conclusions

This review examined literature from a variety of countries and with several different intended uses: some were assessments of different electricity technologies which were then evaluated using multi-criteria decision analysis (MCDA), while others were frameworks proposed for various purposes without being applied to case studies or real data. In total, 24 indicator frameworks were examined in detail following selection from a much larger pool of sustainability studies based on relevance to this research. These 24 frameworks are variously set in the contexts of electricity generation, biofuel production, water mains provision and national sustainable development reporting.

The literature review revealed great variation in the number of indicators, their classification and the issues they address. Regarding the former, of the energy sector-specific assessments reviewed, a range of five [32] to 79 indicators [44] has been used by different authors. However, many of these frameworks are intended for use at a company level, so a large number of their indicators are not applicable to sustainability assessment of technologies. Moreover, numerous indicators encountered in the review are qualitative: despite potentially being highly informative, qualitative indicators are at risk of being subjective or misunderstood if their basis is not explained, as is often the case.

There are also several approaches to the classification of indicators. For example, Hirschberg et al. [40] group impact areas and indicators into 'economy', 'environment' and 'social'. In contrast, Panthi and Bhattarai [70] organise the indicators (referred to as sub-factors) into 'technical', 'social/environmental', 'financial' and 'institutional' categories. However, despite there being no consensus on categorisation, most definitions of sustainable development acknowledge that it must address environmental, social and economic aspects. Classifying indicators into these three groups is the approach taken in most sustainability assessment frameworks [see, for example, 32, 34, 41, 43, 44, 45, 64] and is rooted in the widely used 'three pillars of sustainability' concept, otherwise known as the 'triple bottom line' [83].

Regarding the issues addressed by the indicator frameworks, climate change and investment and/or total cost are the most regularly considered [see, for example, 32, 33-37, 39, 40, 42, 43, 45, 46, 84], although the methods for their quantification differ. For instance, climate change impacts can either be considered simply in terms of carbon dioxide emissions [see 32, 33, 37, 43, 84] or, more thoroughly, in terms of global warming potential, which includes all greenhouse gases converted to a CO_2-equivalent emission [see 34-36, 39, 40-42, 44-46, 50]. Similarly, the measurement of cost varies between undiscounted capital or operational costs [32-34, 37, 40, 42] and total discounted costs [45, 46] or net present value [41, 43]. In many cases it is not clear whether costs have been discounted or not [32, 33, 35-37, 39]. Following these two indicators, employment is the next most commonly considered issue, again using various quantification methods [see 33-36, 40, 41, 43-46, 84].

Beyond these three basic issues, greater variance occurs in terms of coverage, especially of social issues which are sometimes combined into a compound qualitative indicator, often with little explanation of the basis for scoring [see, for example, 39]. Alternatively, several studies make qualitative assessments of highly subjective criteria like visual impact and satisfaction of residents [see, for example, 34, 36, 39, 40, 41]. These kinds of issues are highly controversial, since their evaluation relies not only on the technology under assessment but on factors like the interest level and age of the assessor, as well as various other site- and case-specific factors [85].

Among other issues, the literature review highlighted a general lack of transparency in many of the indicator frameworks reviewed. Examples include failure to specify the system boundaries of each indicator, leading to uncertainty over which parts of the life cycle are included [see, for example, 35, 68], and failure to explain how certain impacts were quantified [see, for example, 36, 41-43, 56]. This latter point is particularly relevant for qualitative impacts which are often scored on an ordinal scale, as is the case for the social indicators mentioned above.

Transparency in sustainability assessments is crucial, particularly given the fact that the key aim of most assessments is to inform a range of stakeholders without bias, facilitating debate and decision making. If it is not clear what has been assessed and how results were derived, or if there is significant reliance on unexplained 'expert judgment' of qualitative aspects, trust in a study's conclusions can be affected, diminishing the impact of the assessment.

The following chapter presents the methodology developed in this project, based on the findings of this review and set in the context of electricity systems.

3 Methodology: a framework for sustainability assessment of electricity generation

The content of this chapter is based on an article by Stamford and Azapagic in the October 2011 edition of Energy [31].

This chapter discusses the sustainability assessment framework produced in this research, the development of which fulfils the main aim of the project. The framework draws on the work of other authors, as discussed in the previous chapter, as well as on stakeholder interaction. This chapter begins with an overview of the methodology and its origins, followed by a discussion of the sustainability issues covered by the framework and the indicators used to address them.

3.1 Methodology overview

It is widely recognised and accepted that sustainability assessments should take a life cycle approach, taking into account relevant techno-economic, environmental and social sustainability issues. Therefore, the framework proposed here follows this approach. This ensures that different electricity options can be considered on an equivalent basis and also allows identification of 'hot spots', indicating opportunities for improvement from 'cradle to grave'.

The proposed methodological framework is outlined in Figure 2 and involves the following main steps:

i. definition of the goal and scope of the sustainability assessment;
ii. selection of the electricity options and identification of possible future electricity scenarios to be assessed;
iii. identification of relevant sustainability issues and definition of related sustainability indicators to enable the assessment; and
iv. assessment of techno-economic, environmental and social sustainability along the life cycle of the electricity options.

This framework builds on previous work by Azapagic and collaborators on sustainability assessment [86, 87] but has been developed further for the purposes of this research and in particular for application to the electricity sector. The main novelty of the framework is development of the life cycle sustainability indicators; these are described in detail in the rest of this chapter. Prior to that, a brief overview of each step is given:

i. In the first step, the goal and scope of the study are defined. This step is similar to the first phase of the life cycle assessment (LCA) methodology [88]. As in LCA, this is a crucial step as it determines the next stages of the study as well as the results. In this research, the main goal has been to assess the sustainability of different electricity options in the UK, both now and in the future, up to the year 2070. This time frame was selected to reflect the long lifespans of electricity options, particularly nuclear plants, as well as to explore beyond the reference year of 2050 normally chosen by other studies (see, for example, UKERC [3] and DECC [29]). Scenario analysis has been chosen as a tool for exploring the sustainability consequences of different possible electricity 'futures' in the UK. As indicated above, a life cycle approach has been adopted for the sustainability assessments so that the scope of the study is from 'cradle to grave'.
ii. The second step involves the identification of the electricity options to be assessed as well as the definition of future scenarios. While ideally all possible options should be considered, this is a huge task and is not feasible for a PhD project with limited duration and resources. Therefore, in this work, a limited number of electricity options have been chosen for consideration. These are nuclear, gas, coal, offshore wind and solar photovoltaics (PV). The choice of the former three technologies has been driven by their current importance in the UK electricity mix. It is also expected that nuclear and gas will continue to play an important role in future electricity supply, together with wind and PV [3, 29, 89]. Carbon capture and storage (CCS) is also considered in conjunction with coal as it is expected that CCS will become available on a moderate to large scale in the 2020s [90]. Gas with CCS has not been considered because the UK CCS programme has, thus far, focused entirely on coal; prospects for gas CCS in the UK are therefore less well established. Other technologies had to be rejected on the grounds of prohibitive technological diversity (biomass), relative lack of expansion opportunities in the UK (hydro) and lower prominence in current UK energy policy than solar and offshore wind (onshore wind, geothermal, combined heat and power, imports). The different technologies and their sustainability are discussed in detail in Chapters 4-8. A number of different future scenarios have been developed, driven by climate change targets (one of

the UK Government's main reasons for promoting more sustainable electricity supply [29]). The scenarios are described and discussed in Chapter 9.

iii. Identification of sustainability issues and development of indicators is carried out in the third step of the methodology. These are related to the technologies chosen for the sustainability assessment and span their whole life cycle (where applicable). The indicators cover all three dimensions of sustainability: techno-economic, environmental and social. A detailed discussion of the indicators is presented further below.

iv. Finally, the technologies are assessed on different aspects of sustainability using the developed indicators. The results are then used to assess the sustainability of different scenarios, which assume different mixes of the technologies assessed. The results of the sustainability assessments can be found in Chapters 4-9.

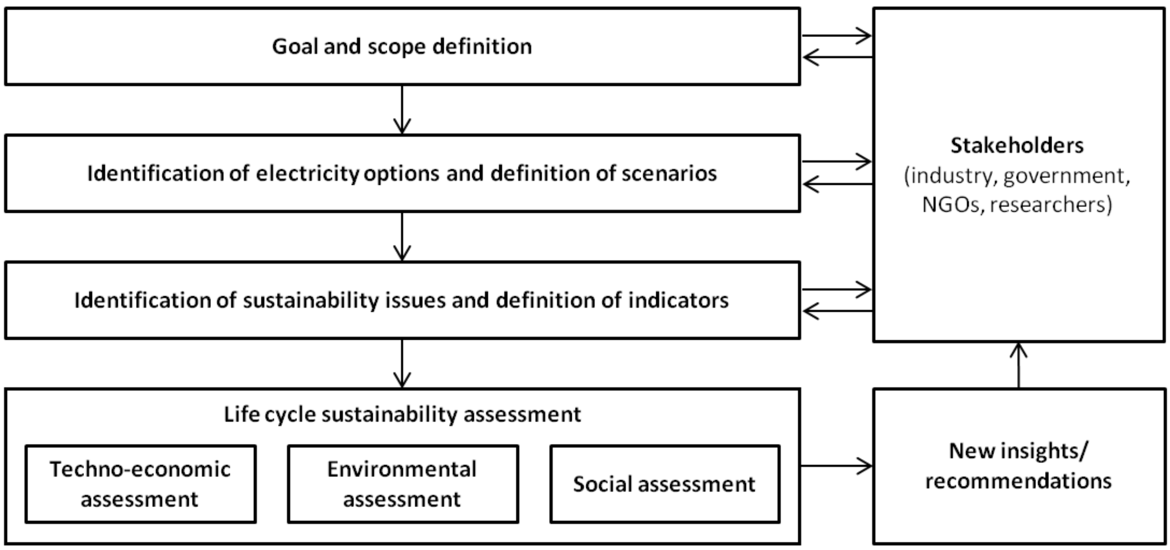


Figure 2: Methodological framework for life cycle sustainability assessment of electricity generation

As indicated in Figure 2, the framework has been developed in collaboration with stakeholders including industry, Government, NGOs and experts from academia. More than 30 stakeholders were involved, representing the organisations listed in Table 1, with collaboration largely conducted via face-to-face interviews. Thus, the developed framework arguably represents the concerns of a broad range of stakeholder groups in the UK.

Government/regulatory	
• Department of Energy and Climate Change	• Environment Agency
• European Commission	• Health and Safety Executive
• Organisation for Economic Co-operation and Development	
Industry	
• Aker Solutions	• AMEC
• Combined Heat and Power Association	• Costain
• EDF Energy	• Horizon Nuclear Power
• Serco	• Solar Trade Association
• Westinghouse	
NGO	
• Chatham House	• Friends of the Earth
• Society for the Environment	
Academia	
• Centre for Ecology and Hydrology	• National Nuclear Laboratory
• University of Central Lancashire	• University of Leeds
• University of Manchester	• University of Southampton

Table 1: Stakeholders consulted during the development of the methodological framework

As mentioned above, the following sections focus on sustainability issues and the indicators developed within this work.

3.2 Sustainability issues and indicators

The sustainability indicators developed in this work and published in [31] are summarised in Table 2, which also shows their relevance to each life cycle stage of electricity generation. There are 42 sustainability indicators addressing six techno-economic, eight environmental and eight social issues. The proposed indicators draw on some of the previous approaches to sustainability assessment discussed in the literature review in Chapter 2 [such as 32-35, 40, 44, 45, 46, 57, 64, 78, 91] as well as on the direct stakeholder input obtained as part of this research.

Discussions of how best to develop sustainability indicators often distinguish between 'top-down' and 'bottom-up' approaches (see, for example, [92]): in the former, indicators are identified by the researchers or practitioners, whereas in the latter they are identified by the affected communities. In this work, the combination of literature review, novel indicator development and stakeholder input attempts to merge both approaches. Throughout the process, the indicators were refined and guided by the following criteria:

- Relevance to electricity generation;
- lack of double-counting (i.e. no two indicators should address the exact same issue);
- clarity of value preference (i.e. indicators should have a directional preference attached to them);
- quantifiability; and
- feasibility given reasonable constraints on time and data.

Although the indicators are divided into techno-economic, environmental and social categories, it is acknowledged that this is somewhat an artificial division, as in all other sustainability assessment frameworks, due to the inherent interconnections between different issues and their respective indicators.

Calculations for estimation of the indicators are given throughout the text and are listed together in Appendix 2.

As mentioned above, the indicators discussed below are based on the work published by the author of this dissertation [31]. However, there, the focus was on nuclear power whilst here the indicators are more general and applicable to different technologies, including those considered in this work.

Table 2: Proposed indicators and their applicability to the stages of a generic electricity production life cycle

Category	Issue addressed	Indicator	Unit	Life Cycle Stage: Construction	Fuel Mining & Processing	Operation	Waste Disposal	Decommissioning
Techno-economic	Operability	1. Capacity factor (power output as a percentage of the maximum possible output)	Percentage (%)	-	-	✓	-	-
		2. Availability factor (percentage of time a plant is available to produce electricity)	Percentage (%)	-	-	✓	-	-
		3. Technical dispatchability (ramp-up rate, ramp-down rate, minimum up time, minimum down time)	Summed rank	-	-	✓	-	-
		4. Economic dispatchability (ratio of capital cost to total levelised generation cost)	Dimensionless	✓	✓	✓	✓	✓
		5. Lifetime of global fuel reserves at current extraction rates	Years	-	-	✓	-	-
	Technological Lock-in	6. Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/thermochemical H_2 production) and operational lifetime	$Years^{-1}$	-	-	✓	-	-
	Immediacy	7. Time to plant start-up from start of construction	Years	✓	-	-	-	-
	Levelised Cost of Generation	8. Capital costs	Pence/kWh	✓	-	-	-	✓
		9. Operation and maintenance costs	Pence/kWh	-	-	✓	✓	-
		10. Fuel costs	Pence/kWh	-	✓	-	-	-
		11. Total levelised cost	Pence/kWh	✓	✓	✓	✓	✓
	Cost Variability	12. Fuel price sensitivity (ratio of fuel cost to total levelised generation cost)	Dimensionless	✓	✓	✓	✓	✓
	Financial Incentives	13. Financial incentives and assistance (e.g. ROCs, taxpayer burdens)	Pence/kWh	✓	-	✓	✓	✓
Environmental	Material Recyclability	14. Recyclability of input materials	Percentage (%)	✓	-	-	-	✓
	Water Eco-toxicity	15. Freshwater eco-toxicity potential	kg 1,4 DCB‡ eq./kWh	✓	✓	✓	✓	✓
		16. Marine eco-toxicity potential	kg 1,4 DCB‡ eq./kWh	✓	✓	✓	✓	✓

	Global Warming	17. Global warming potential (GHG emissions)	kg CO_2 eq./kWh	✓	✓	✓	✓	✓
	Ozone Layer Depletion	18. Ozone depletion potential (CFC and halogenated HC emissions)	kg CFC-11 eq./kWh	✓	✓	✓	✓	✓
	Acidification	19. Acidification potential (SO_2, NO_x, HCl and NH_3 emissions)	kg SO_2 eq./kWh	✓	✓	✓	✓	✓
	Eutrophication	20. Eutrophication potential (N, NO_x, NH_4^+, PO_4^{3-} etc.)	kg PO_4^{3-} eq./kWh	✓	✓	✓	✓	✓
	Photochemical Smog	21. Photochemical smog creation potential (VOCs and NO_x)	kg C_2H_4 eq./kWh	✓	✓	✓	✓	✓
	Land Use & Quality	22. Land occupation (area occupied over time)	m^2yr/kWh	✓	✓	✓	✓	✓
		23. Greenfield land use (proportion of new development on previously undeveloped land relative to total land occupied)	Percentage (%)	✓	-	-	-	-
		24. Terrestrial eco-toxicity potential	kg 1,4 DCB[‡] eq./kWh	✓	✓	✓	✓	✓
Social	**Provision of Employment**	25. Direct employment	Person-years/GWh	✓	-	✓	-	✓
		26. Total employment (direct + indirect)	Person-years/GWh	✓	✓	✓	✓	✓
	Human Health Impacts	27. Worker injuries	No. of injuries/TWh	✓	✓	✓	✓	✓
		28. Human toxicity potential (excluding radiation)	kg 1,4 DCB[‡] eq./kWh	✓	✓	✓	✓	✓
		29. Human health impacts from radiation (workers and population)	DALY[¥]/GWh	✓	✓	✓	✓	✓
	Large Accident Risk	30. Fatalities due to large accidents	No. of fatalities/GWh	✓	✓	✓	✓	✓
	Local Community Impacts	31. Proportion of staff hired from local community relative to total direct employment	Percentage (%)	-	-	✓	-	-
		32. Spending on local suppliers relative to total annual spending	Percentage (%)	-	-	✓	-	-
		33. Direct investment in local community as proportion of total annual profits	Percentage (%)	-	-	✓	-	-
	Human Rights and Corruption	34. Involvement of countries in the life cycle with known corruption problems (based on Transparency International Corruption Perceptions Index)	Score (0-10)	✓	✓	✓	✓	✓
	Energy Security	35. Amount of imported fossil fuel potentially avoided	toe/kWh	-	-	✓	-	-

	36. Diversity of fuel supply mix	Score (0-1)	-	-	✓	-	-
	37. Fuel storage capabilities (energy density)	GJ/m^3	-	✓	✓	-	-
Nuclear Proliferation	38. Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	Score (0-3)	✓	✓	✓	✓	✓
Intergenerational Equity	39. Use of abiotic resources (elements)	kg Sb eq./kWh	✓	✓	✓	✓	✓
	40. Use of abiotic resources (fossil fuels)	MJ/kWh	✓	✓	✓	✓	✓
	41. Volume of radioactive waste to be stored	m^3/kWh	-	-	-	✓	-
	42. Volume of liquid CO_2 to be stored	m^3/kWh	-	-	-	✓	-

‡DCB – dichlorobenzene; ¥DALY – disability-adjusted life years

3.2.1 Techno-economic issues and indicators

Techno-economic aspects are arguably some of the most important factors for consideration in any sustainability assessment as they determine how well and in what way a technology can be integrated into the electricity mix. If, for example, reliability of a technology is poor, other generators will be needed to compensate for the inoperable unit(s), potentially changing the overall impacts of electricity generation dramatically. Equally, in a competitive market, financial viability is a prerequisite. However, the overall cost of an electricity option is not the only important consideration. Firstly, the cost structure (how much cost is attributable to capital, operation and other relevant stages) can affect viability and the resultant operational characteristics. Secondly, economic impacts of electricity generation are broader than this, including possible taxpayer burdens.

To account for the above factors, the following categories of techno-economic indicators have been identified in this work as most important for nuclear and other electricity-generating technologies:

- operability;
- technological lock-in;
- immediacy;
- levelised cost of generation;
- cost variability; and
- financial incentives.

3.2.1.1 Operability

Operability concerns the way in which a technology works within an integrated electricity mix. As large-scale electricity storage in the UK is currently limited to the 2.7 GW of pumped storage capacity installed [16], generation is mostly dictated by demand which fluctuates minute by minute. Therefore, generation must be managed to follow that demand, and this depends on the technical abilities of the generating fleet. To capture the different technological properties needed for smooth operation of the grid, the indicators considered here are:

- capacity factor;
- availability factor;
- technical and economic dispatchability; and

- lifetime of fuel reserves at current extraction rates.

They all apply to the operational stage of the power plant, although economic dispatchability requires consideration of full life cycle costs (see Table 2).

Capacity factor is the power output of a plant in a specified time expressed as a percentage of the maximum possible power output over the same time period had the plant been running continuously at full power [18], as follows:

$$CF = \frac{P_{\text{out}}}{P_{\max}} \times 100 \quad (\%) \qquad (1)$$

CF – capacity factor (%)

P_{out} – power output of a plant (MWh)

$P_{\max}$ – maximum possible power output (MWh)

It should be noted that capacity factor may vary from one time period to the next as the operator responds to external factors like changes in fuel price or baseload requirements. There may not, therefore, always be a preference associated with capacity factor. However, capacity factor does give an indication of the capabilities and characteristics of a technology. For instance, nuclear power, as discussed in Section 3.2.1.4, has relatively high capital costs and low fuel costs, meaning it is advantageous to run the plant at consistently high loads, giving a high capacity factor (around 86% for Sizewell B [19]). A lower capacity factor at a nuclear plant therefore suggests reliability problems, as is the case in the older AGR fleet (50.2% fleet average in 2008 [calculated from 19]). In the case of wind power, capacity factors are typically 25-35% [16], with higher capacity factors suggesting excellent site characteristics and/or turbine reliability.

Availability factor is the percentage of time in which a plant is available to produce electricity [18], as follows:

$$A = \frac{t_A}{t_{\max}} \times 100 \quad (\%) \qquad (2)$$

A – plant availability (%)

t_A – time over which the plant is available for generation of electricity over one year (hrs/yr)

$t_{\max}$ – maximum operating time over one year (hrs/yr)

This is fundamentally different to capacity factor as it includes times when the plant is fully functioning but is not being used. As such, it is a general measure of reliability. In the case of nuclear power, the operational fuel cycle of light water reactors typically necessitates a period of (very roughly) 40 days every 18 months in which the reactor must be shut down to refuel [93], giving a highest theoretical availability factor of around 93%. Technologies that do not require shutting down to refuel may be able to achieve higher availability factors, although maintenance requirements and unforeseen down time normally preclude this.

Dispatchability is the ability of a generating unit to increase or decrease generation, or to be brought online or shut down as needed [94]. This is a difficult characteristic to evaluate succinctly, being determined by many technical and economic characteristics. Therefore two indicators are proposed: *technical dispatchability* and *economic dispatchability*. The former applies only to the operational stage and can be determined by ramp-up rate, ramp-down rate, minimum up time and minimum down time[5]. For instance, open cycle gas turbines (OCGTs) typically have ramp-up rates of 90-100% of maximum power (P_{max}) per minute, coupled with minimum down times of eight to ten minutes [95]. As a result, they can change their output quickly and need only short periods offline before being started again. In contrast, due to their greater complexity and thermal constraints, combined cycle gas turbines (CCGTs) typically have ramp-up rates of around 2-3% P_{max} per minute and minimum down times of 300 minutes [95]. Modern nuclear power stations are able to follow load reasonably well: some reactors in the current French fleet reduce their output to 25% of maximum every day [96]. Similarly, the Westinghouse AP1000 claims a ramp-up rate of 5% per minute [97], which compares favourably with a typical coal power station [98]. It is suggested that the technologies should be ranked on each of the four technical criteria described above (ramp-up rate, ramp-down rate, minimum up time and minimum down time), with the rankings subsequently summed to derive a total technical dispatchability ranking, as follows:

$$TD = R_{RUR} + R_{RDR} + R_{MUT} + R_{MDT} \quad (-) \qquad (3)$$

TD – technical dispatchability value (-)
R_{RUR} – ranking for ramp-up rate
R_{RDR} – ranking for ramp-down rate
R_{MUT} – ranking for minimum up time
R_{MDT} – ranking for minimum down time

[5] Ramp-up and ramp-down rates are the rates at which a unit can increase and decrease, respectively, its power output, expressed as a percentage of maximum power per minute. Minimum up and down times are the minimum times (in minutes or hours) during which a unit must carry on generating or not generating power, respectively, before being switched off or started up. This is generally in order to avoid breaching thermal stress constraints, the aim being to avoid serious maintenance requirements.

In some cases, technical ability to follow load does not translate into actual load-following behaviour. For instance, the high capital and low operating costs of nuclear plants mean that it is normally uneconomic to vary output: the cost profile means that generating at maximum capacity is desirable at all times in order to reduce the payback time. Therefore, this framework quantifies economic dispatchability based on the life cycle costs of electricity generation: the ratio of capital cost to total levelised cost (see Section 3.2.1.4) expresses the economic detriment of load-following, where low ratios suggest technologies better suited to varying output:

$$ED = \frac{CC}{LEC} \quad (-) \qquad (4)$$

ED – economic dispatchability (-)
CC – capital component of total levelised costs (pence/kWh)
LEC – levelised electricity costs (pence/kWh)

The fact that this is based on total levelised costs means the whole life cycle must be considered. Approximately 70% of the levelised cost of nuclear electricity arise from capital costs, whereas this figure is normally less than 20% for CCGTs [99]. This is reflected in the typical decision of current utility companies to use nuclear stations exclusively for baseload while CCGTs operate on intermediate load cycles.

The *lifetime of fuel reserves at current extraction rates* is a reflection of current usage rates compared to identified economically recoverable resources:

$$LFR = \frac{ERR}{UR} \quad \text{(years)} \qquad (5)$$

LFR – lifetime of fuel reserves (years)
ERR – economically recoverable resources (t)
UR – current usage rates of fuels (t/yr)

Figures currently stand at approximately 100 years for uranium [100], 120 years for coal [101], 55 years for natural gas and 41 years for oil [102] (although of course these quantities depend on what is classed as economic to extract). The indicator is a best estimate of the global longevity of fuel supplies, but is accompanied by unavoidable caveats. It does not try to predict any changes in demand which might occur over the coming decades; nor does it consider future reserve discoveries or improvements in extraction technology that would make currently uneconomic reserves exploitable. In the context of electricity production, it also assumes that fuels currently used to provide several services (such as natural gas, which is used for heating as well as electricity) continue to be allocated between those services in their current proportions. It should also be noted that certain fuels (primarily fossil) have been the subject of more extensive exploration than others, meaning that the estimated lifetimes of fossil fuel reserves are probably more realistic than those of, for example, uranium. This is reflected in the fact that investment in uranium exploration was very low from 1980 to 2003, but is now increasing, making it likely that the current economically recoverable reserves are underestimated [100, 103].

3.2.1.2 Technological lock-in

This indicator, also applicable to the operational stage, describes situations which cause an economic system "gradually to lock itself in to an outcome not necessarily superior to alternatives, not easily altered, and not entirely predictable in advance" [104]. In the context of electricity generation, this can be interpreted as the extent to which a choice of technology in the present day prohibits future changes in energy provision. For example, it is often argued that the development of large, centralised power stations with long lifespans might be expected to subdue the growth of small-scale, decentralised power generation [see, for example, 105]. This is because the former situation 'locks' the energy system into a regime which has characteristics that do not favour widespread small-scale generation: for instance, the existence of large utility companies and an extensive, well maintained national grid would, arguably, not be required at such a scale if decentralised generation had dominated the market at an earlier stage.

Clearly this is a difficult subject to address from the perspective of present-day energy choices: as already mentioned, the attributes of a locked-in system are not entirely predictable in advance. Moreover, attempts to explain technological lock-in tend to ascribe it primarily to social and economic phenomena rather than to characteristics of the technologies themselves. Examples include the bounding of thought by 'incremental' innovation [106], increasing returns to adoption (the preference to adopt technologies that are already widespread, or at least perceived to be) [104, 107] and the network externalities caused by technological 'clusters' whereby one technology becomes linked in some way to others, giving it an advantage through association [106-108] rather than to characteristics of the technologies themselves. Due to these immeasurable complexities, two basic, measurable criteria are suggested instead that nevertheless have a significant effect, at the technological level, on lock-in: lifespan and flexibility.

The former criterion is relatively easy to quantify in terms of years of expected lifetime. The latter is slightly more subjective, but can be described in terms of the ability to cater for different energy requirements, if needed, in the future. Key abilities that may be useful in the future – identified by the stakeholders involved in this research – include the potential to provide heating and cooling as well as electricity (trigeneration), to operate with net negative carbon emissions (by burning biomass with CCS), and to produce hydrogen via thermal/thermo-chemical processes for use in fuel cells.

A high degree of flexibility and a short lifespan are preferable from the perspective of technological lock-in: the former allows for changes in energy provision during the life of the plant, while the latter reduces the inertia of the system by diminishing economic ties to legacy assets and providing more points at which new technologies can be brought online [109]. Naturally, a short lifespan is not preferred from the investment point of view for capital-intensive technologies such as nuclear; however, this indicator does not attempt to capture the cost aspects, which are addressed by different indicators, as discussed further below.

Therefore it is suggested that the lock-in indicator be defined as a ratio of the square of the flexibility index and the lifespan of technology, as follows:

$$T = \frac{f^2}{l} \quad \text{(years}^{-1}\text{)} \qquad (6)$$

T - technological lock-in score (years^{-1})
f - flexibility index (0-30)
l - lifespan of the technology (years)

The 'flexibility index' is scored on an ordinal scale (0 - 30)[6] in which the three key services identified above (trigeneration, negative CO_2 emissions and H_2 production) are allocated 10 points each. This equal scoring is suggested because the index attempts to account for overall flexibility rather than to predict which of the services will be most important in the future. The index is then squared to reduce the indicator's sensitivity to technology lifespan.

As an example, a PWR reaches temperatures of around 325°C [110], much of which is wasted, and could therefore provide trigeneration, assuming any acceptance issues surrounding proximity to the reactor and use of nuclear heat were overcome. However, significantly higher temperatures are required for thermal hydrogen production, and nuclear power cannot provide

[6] The scale is rather arbitrary and has been chosen simply to provide overall indicator results greater than one. Changing the scale does not affect the relative score of a technology.

negative CO_2 emissions. Its flexibility index is therefore 10. With a lifespan of 60 years [20, 21], its technological lock-in score is 1.67 ($T = 10^2 \div 60$). In contrast, a theoretical biomass CCS power plant might be able to provide trigeneration and negative net carbon emissions while operating at a high enough temperature to produce hydrogen thermally. This gives a flexibility index of 30. Given a lifetime of 40 years, this yields a technological lock-in score of 22.5 ($T = 30^2 \div 40$). Therefore, in terms of technological lock-in, the biomass CCS plant would be more sustainable than the PWR.

3.2.1.3 Immediacy

Immediacy addresses the potential problems caused by technologies with long lead times. Therefore, this indicator is defined here as the overall time taken from the start of construction to start-up of the plant and is thus relevant to the construction stage of a power plant. For instance, the so-called UK 'energy gap', resulting from the retirement of older nuclear power stations and the effect of the European Large Combustion Plant Directive (directive 2001/80/EC), is likely to begin in 2016 when combustion plants that opted out of the above directive will be forced to close [7]. Given that nuclear power stations have long construction times (generally five to seven years without additional licensing considerations [99, 111]), none can be completed by then because, as of 2012, no new build has started. This makes the option of new nuclear build less useful in situations where generating capacity is required in the near-term. In contrast, a large CCGT is likely to take three to four years to complete [see, for instance, 112], providing a much quicker response to changing power requirements.

3.2.1.4 Levelised cost of generation

The levelised electricity cost (LEC) represents the average price that consumers would have to pay for the investor to break even. It is calculated as the ratio of total costs of generation and the total electricity generated during the lifetime of a power plant, taking into account an appropriate discounting factor [113], as follows:

$$LEC = \frac{\sum_{n=1}^{N} \frac{CC_t + M_t + F_t}{(1+r)^t}}{\sum_{n=1}^{N} \frac{E_t}{(1+r)^t}} \times 10^{-2} \text{ (p/kWh)} \quad (7)$$

LEC – levelised electricity cost (p/kWh)

CC_t – capital costs (investment) in year t (£)

M_t - operations and maintenance expenditure in year t (£)

F_t - fuel expenditure in year t (£)

E_t - electricity generation in year t (kWh)

r - discount rate

N – lifetime of the power plant

Therefore, the LEC is relevant to the whole life cycle of the power plant (see Table 2). Table 3 gives examples of the LEC ranges for some generating technologies in the UK for 2010 [114]. As can be seen, these data show nuclear, CCGT and biomass power plants to be the cheapest options with LECs ranging from 5.5 to 12 pence/kWh. However, in the case of nuclear power, around 70% of the LEC is due to capital costs; in contrast, the main contributor to the costs of power from CCGTs and biomass is fuel (70%). The other renewables have higher levelised costs, ranging from a low estimate of 8 pence/kWh for wind to a high estimate of 39 pence/kWh for tidal. Similarly to nuclear, capital investment contributes more than 70% of the LEC [114].

Table 3: Levelised energy costs for different generating technologies in the UK for 2010 [114] (discount rate = 10%)

Technology	Cost range (pence/kWh)
Nuclear	5.5-8.5
CCGT	5.5-11.0
CCGT with CCS	6.0-13.0
Onshore wind	8.0-11.0
Biomass	6.0-12.0
Coal with CCS	10.0-15.5
Offshore wind	15.0-21.0
Tidal power	15.5-39.0

Obviously, LECs are sensitive to the discount rate assumed. This is illustrated by Figure 3, which is based on the IEA's projection of costs of different technologies [99]: as nuclear power is dominated by capital costs and has relatively low operational costs, raising the discount rate from 5% to 10% dramatically changes its LEC, while that of coal or gas remains similar. It is important, therefore, to state explicitly the discount rate used for estimation of LEC.

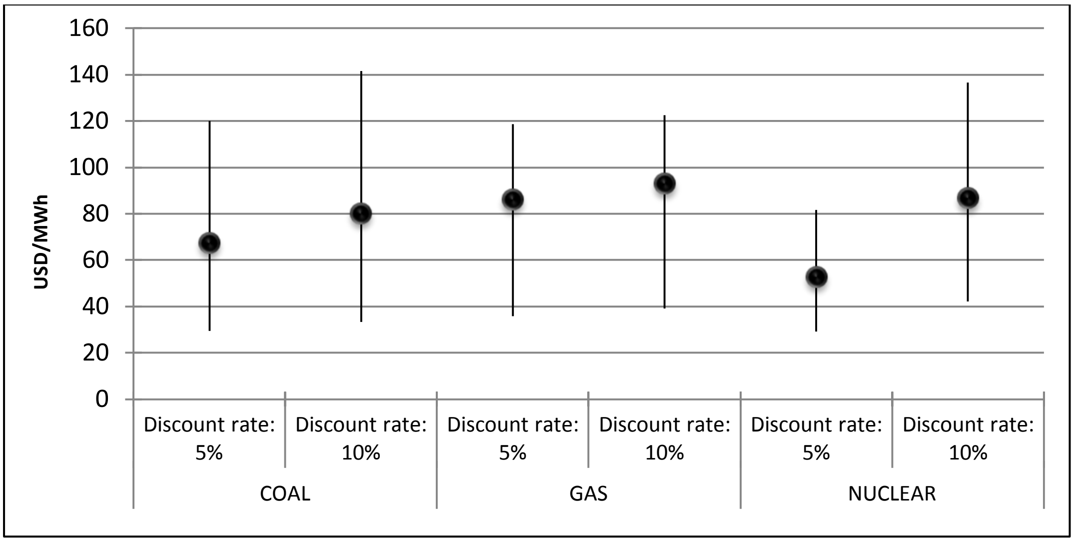


Figure 3: Levelised cost estimate ranges and medians for coal, gas and nuclear power at 5% and 10% discount rates (based on data from the IEA [99])

Discounting rates are also a controversial topic in sustainable development, as they effectively neglect costs (and benefits) experienced by future generations (for discussion, see for instance [115]). An alternative approach would be to avoid discounting completely by giving undiscounted costs for different life cycle stages: Polatidis and Haralambopoulos [43] and Cavallaro and Ciraolo [116], for example, use undiscounted installation costs and operational costs in their sustainability assessments. However, there are at least two advantages to using discount rates, both pragmatic. Firstly, power stations in the UK are privately owned and operated (although some public contribution may exist), meaning they will be commissioned or otherwise on a market basis. In this context, making decisions based on a very low (or zero) discount rate is economically unrealistic as it neglects both the opportunity cost of investment and the financial risk to the investor. Secondly, the fact that all businesses incorporate discounting into their decision making processes means that an assessment without discounting is less communicable. It is suggested, however, that several discount rates might be used as part of sensitivity analysis to explore the interaction between economic costs and intergenerational issues. Low discount rates are favoured if the goal is to avoid transferring costs to future generations; this in turn favours high capital, low running cost options such as nuclear power and most renewables. In contrast, high discount rates diminish future costs and accentuate near-term costs, thereby favouring options with less capital investment but higher running costs.

It should be noted that the separate cost components (capital, O&M, fuel and total costs) are treated as individual indicators within the methodology (see Table 2). However, if the results of an assessment are to be used in multi-criteria decision analysis (MCDA), it is important to avoid double counting with other related indicators such as fuel price sensitivity (see below); consequently, only the total levelised cost should be used in MCDA.

3.2.1.5 Cost variability

Fuel price volatility and its impact on cost variability of energy have been identified as major drivers of UK energy policy [111, 117]. Fuel price sensitivity as an indicator of cost variability has been included in at least two previous sustainability assessments of electricity-generating options [40, 45]. It is expressed as the ratio of fuel cost to total levelised electricity cost, providing a measure of financial risk due to price fluctuations:

$$CV = \frac{FC}{LEC} \quad (-) \qquad (8)$$

CV – fuel cost variability (fuel price sensitivity) (-)
FC – fuel cost (p/kWh)
LEC – levelised electricity costs (p/kWh)

Therefore, as shown in Table 2, it is relevant to the whole life cycle of a power plant. Its value varies greatly between different technologies. For example, using IEA data [99], the mean estimated levelised costs of coal and gas electricity in the OECD countries are 77 and 86 USD/MWh respectively (at 10% discount rate, without carbon tax), of which 27 and 64 USD/MWh are fuel costs. This gives coal a fuel price sensitivity of 0.35 and gas 0.74, figures which are broadly in line with other estimates [such as 113, 118, 119]. The difference between the two is a result of significantly higher capital costs associated with coal plants [99]. In contrast to both cases, fuel costs only constitute around 10% of overall costs for nuclear power [111, 113], meaning fuel price fluctuations have a very limited impact. This effect is amplified by the fact that a large proportion of the fuel cost is due to fuel processing, with less than half being the actual cost of uranium [120]. This contrasts with other fuels because uranium undergoes many processing stages (mining, milling, conversion, enrichment and fuel fabrication) before usable fuel assemblies are sold to power plant owners. Fossil fuels, on the other hand, involve only the processing of the fuel itself, meaning fuel price fluctuations are buffered less by subsequent processing steps.

3.2.1.6 Financial incentives

This indicator takes account of non-market financial incentives and assistance for the generation of electricity in the UK. It therefore includes all subsidies incurred at the development, construction, operation, decommissioning and waste disposal stages and is expressed in pence/kWh (see Table 2). With global energy subsidies (direct and indirect) estimated at US$ 300 billion per year, of which around 77% goes to fossil fuels [121], concerns are often voiced over their distribution between different technologies, and whether this constitutes a fair market. Nuclear, renewables and fossil fuels have all been subject to criticism in this respect [see, for example, 122, 123-125].

In general, two types of incentives can be distinguished: regulatory tools used by government to drive the market in a particular direction and hidden subsidies that are not used as market tools. Regarding the first component, in the UK context the main considerations are therefore the Renewables Obligation Order (RO), the Feed-in Tariff (FiT), the carbon cost avoided by low-carbon generators and any direct payments from government to generators (such as in the newly proposed 'contract for difference' system in which the government would guarantee long-term feed-in tariffs, topping up payments with public money [126]). However, the issue is complicated by many factors, including: state funding of legacy assets and operations (such as the eventual decommissioning and disposal of UK nuclear liabilities, estimated by the NDA to cost £44.5 billion [127]); the global nature of the subsidies, meaning imported fuels are subsidised differently depending on their origin; and historical support enjoyed by previously nationalised industries. The latter often serves as a supporting argument for renewables which, as incumbent technologies, have not benefitted from the subsidies given to the non-renewables that dominated electricity markets prior to their widespread decentralisation in the 1990s [121].

Regarding the second component of this indicator (hidden subsidies), this includes:

- any insurance caps, whereby owners of plants are not required to insure their full liability (see Section 4.4.1.6);
- the administrative cost of technology-specific market tools (ROCs, FiT and carbon price);
- publically funded site selection studies;
- Health and Safety Executive design assessments;
- increased maintenance costs incurred by thermal power plant owners as they are forced to run their plants more variably to compensate for intermittent renewables on the grid; and

- the costs of increased system reserve due to intermittent renewables and single large capacity plants on the grid.

Unfortunately, most of these hidden subsidies have not been analysed thoroughly for the UK, meaning they cannot be included in the results presented here. Much further work is needed in this area, in part due to a lack of data but also due to problems of allocation and uncertainty, for example, where subsidies are applied to more than one technology simultaneously or may not be applied in certain cases. As a result, this indicator currently includes only the costs of the aforementioned regulatory tools (RO, FiT, carbon price and any other direct payments).

3.2.2 Environmental issues and indicators

Electricity generation contributes around a third of the UK's carbon emissions [128] and, along with road transport, is the UK's biggest source of environmental pollution [129]. This is despite the fact that electricity only supplies 18% of UK energy demand [130]. It is important to consider all environmental impacts despite the current focus on global warming, as trade-offs often apply. For instance, at the time the UK Low Carbon Transition Plan was published in 2009, it was estimated that its proposals would increase NO_x emissions and therefore acidification and human health impacts [129].

To ensure as broad a coverage as possible of environmental impacts, the following environmental indicators, also commonly considered in LCA, are included in this sustainability assessment framework (see Table 2):

- material recyclability;
- water eco-toxicity;
- global warming potential;
- ozone layer depletion potential;
- acidification potential;
- eutrophication potential;
- photochemical smog creation potential; and
- land use and quality.

They span the whole life cycle of electricity generation and are estimated using life cycle assessment (LCA) as a tool, following the CML 2001 impact assessment method [59]. The CML method has been chosen because it is one of the most widely used life cycle impact assessment

(LCIA) methods and is frequently updated as new life cycle inventory data and characterisation factors become available. The fact that it is widely used means that results can be more easily verified against other research. It is also based primarily on European data, making it more suitable in the current application than certain other methods (such as TRACI, which is of American origin [131]). Finally, CML is a 'midpoint' LCIA method and therefore carries much less uncertainty than 'endpoint' alternatives, such as Eco-indicator 99 [60]: for instance, Eco-indicator 99 expresses climate change (and other human health-related impacts) in terms of disability-adjusted life years. This necessitates considerable assumptions about the future impacts of climate change, the future GHG emissions of the rest of the world and our ability to adapt to climate impacts. Thus, despite being more easily communicable, endpoint LCIA methods are much less robust.

In this study, the only environmental indicators not based on the CML method are material recyclability and some parts of the land use and quality indicator group, as they are not included by CML; these are explained below.

3.2.2.1 Material recyclability

This indicator measures the extent to which materials used in the construction of a power plant are recycled and is therefore relevant to the construction and decommissioning parts of the life cycle. It is calculated as the total percentage (by mass) of the power plant that is recyclable, as follows:

$$MR = \frac{\sum_{j}^{J} R_j}{M_p} \times 100 \quad (\%) \qquad (9)$$

MR – overall material recyclability (%)

R_i – amount of material j that can be recycled (t)

M_p – total amount of materials contained in the power plant (t)

Certain materials, such as steel, aluminium and glass, can be recycled many times without significant loss of quality [132, 133]. In contrast, materials such as concrete can only be partially recycled, for example, by being broken down into aggregate and used for construction [134]. Consequently, certain technologies offer a far greater potential to be recycled than others, ultimately reducing resource consumption and increasing sustainability of materials. In most wind turbines, for example, steel is by far the dominant material, being used for the foundations, tower and various nacelle components [135, 136]. This contrasts with a nuclear power station, which uses predominantly concrete [137], reducing its recyclability (although some of the other materials are not recyclable anyway due to their acquired radioactivity).

3.2.2.2 Water eco-toxicity

Electricity generation accounts for over 50% of all water usage in the industrialised and developing world [138]. Impacts on water quality are diverse, ranging from the emission of toxic compounds to temperature increase. Two indicators are proposed to account for these impacts: freshwater and marine eco-toxicity potentials (Table 2), which are based on the maximum tolerable concentrations of toxic substances by different organisms in freshwater and marine environments. They are expressed in 1,4-dichlorobenzene (DCB) equivalents per kWh and are calculated according to the CML method [139] as follows:

$$FWETP = \sum_{j=1}^{J} FWETP_j \times B_j \qquad (10)$$

(kg 1,4-DCB eq./kWh)

$FWETP$ – total freshwater eco-toxicity potential of energy technology (kg 1,4-DCB eq./kWh)

$FWETP_j$ – freshwater eco-toxicity potential of substance j (kg 1,4-DCB eq./kg)

$$METP = \sum_{j=1}^{J} METP_j \times B_j \qquad (11)$$

(kg 1,4-DCB eq./kWh)

$METP$ – total marine eco-toxicity potential of energy technology (kg 1,4-DCB eq./kWh)

$METP_j$ – marine eco-toxicity potential of substance j (kg 1,4-DCB eq./kg)

B_j – emission of substance j to freshwater or seawater (kg/kWh)

J – total number of toxic species

3.2.2.3 Global warming

With the introduction of the Climate Change Act, which legally binds the UK to an 80% carbon emission reduction by 2050, global warming has become a key driver of UK energy policy. The low carbon emissions of nuclear power and renewables are the main reason for high interest in these technologies.

As global warming has wide-ranging impacts, both intra- and intergenerational, affecting the environmental, society and the economy, it is perhaps best described as an integrated indicator [64]. However, due to its inclusion as an environmental indicator in LCA, it is considered under the environmental category within this framework. Global warming potential (GWP) expresses the potential of different greenhouse gases (GHGs) to cause climate change. GWP factors for different GHGs are expressed relative to the GWP of CO_2, which is defined as unity. It is calculated as:

$$GWP = \sum_{j}^{J} GWP_j \times B_j \qquad (12)$$

(kg CO_2 eq./kWh)

GWP – total GWP of energy technology (kg CO_2 eq./kWh)

GWP_j – GWP factor for GHG j (kg CO_2 eq./kg)

B_j – emission of GHG j (kg/kWh)

J – total number of GHGs

The values of GWP depend on the time horizon over which the global warming effect is assessed. GWP factors for shorter times (20 and 50 years) provide an indication of the short-term effects of greenhouse gases on the climate, while GWP for longer periods (100 and 500 years) are used to predict the cumulative effects of these gases on the global climate. GWP100 is used more widely and therefore within this framework.

3.2.2.4 Ozone layer depletion

Ozone layer depletion refers to the thinning of the stratospheric ozone layer by chlorofluorocarbons (CFCs), which results in increased transmission of UVB radiation to the Earth's surface. Despite the ban of CFCs under the Montreal Protocol [140] some ozone depleting substances are still manufactured in various non-signatory countries for use in signatory countries. As such, ozone depletion is still a relevant issue.

Ozone layer depletion potential (ODP) indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and other halogenated hydrocarbons to deplete the ozone layer. It is expressed relative to the ozone depletion potential of CFC-11 and calculated as:

$$ODP = \sum_{j}^{J} ODP_j \times B_j \qquad (13)$$

(kg CFC-11 eq./kWh)

ODP – total ozone layer depletion potential of energy technology (kg CFC-11 eq./kWh)

ODP_j – ODP of ozone depleting gas j (kg CFC-11 eq./kg)

B_j – emission of ozone depleting gas j (kg/kWh)

J – total number of ozone depleting substances

3.2.2.5 Acidification

Acidification causes increased mortality of aquatic organisms in lakes and rivers as well as erosion of buildings due to emissions of acid gases such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), hydrogen chloride (HCl) and ammonia (NH_3). Power generation has been identified as responsible for affecting species composition at several sites in the UK, often reducing overall biodiversity (see, for example, [141]).

Acidification potential (AP) is expressed relative to the AP of SO_2 and calculated according to the equation:

$$AP = \sum_{j}^{J} AP_j \times B_j \qquad (14)$$

(kg SO_2 eq./kWh)

AP – overall acidification potential of energy technology (kg SO_2 eq./kWh)

AP_j – acidification potential of acid gas j (kg SO_2 eq./kg)

B_j – emission of acid gas j (kg/kWh)

J – total number of acid gases

3.2.2.6 Eutrophication

Eutrophication refers to the promotion of biomass growth in an ecosystem owing to an influx of nutrients such as nitrogen and phosphorus. This depletes local oxygen and affects aquatic organisms. Currently, in the UK, critical loads are exceeded in 60% of habitats sensitive to eutrophication from nitrogen deposition [129]. This has also been highlighted, along with acidification, as an issue of increasing importance given that power stations with CCS release more NO_x and NH_3 than current fossil fuel stations [142]. The main cause of this is oxidation of the monoethylamine solvent used in the carbon capture process. Given the potential future prominence of CCS in power generation, this is an important consideration.

Eutrophication potential (EP) is expressed relative to PO_4^{3-} and calculated as:

$$EP = \sum_{j}^{J} EP_j \times B_j \qquad (15)$$

(kg PO_4^{3-} eq./kWh)

EP - overall eutrophication potential of energy technology (kg PO_4^{3-} eq./kWh)

EP_j – eutrophication potential of nutrient j (kg PO_4^{3-} eq./kg)

B_j – emission of nutrient j (kg/kWh)

J – total number of nutrients

3.2.2.7 Photochemical smog

It has been estimated that, in the year 2000, ground level ozone (the main constituent of photochemical smog) caused €6.7 billion of lost arable crop production in the EU [143]. NO_x, volatile organic compounds (VOCs), CH_4 and CO are all ozone precursors, with power generation mainly contributing via NO_x: power stations produce around 20% of anthropogenic NO_x emissions in the UK [143]. As is the case with eutrophication, this is of particular interest if coal CCS becomes widespread, due to its higher NO_x emissions [142].

This indicator is expressed relative to the photochemical ozone creation potential (POCP) of ethylene and can be calculated as:

$$POCP = \sum_{j}^{J} POCP_j \times B_j \qquad (16)$$

(kg C_2H_4 eq./kWh)

$POCP$ – total photochemical oxidant creation potential of energy technology (kg ethylene eq./kWh)

$POCP_j$ – POCP potential of species j (kg C_2H_4 eq./kg)

B_j – emission of substances j contributing to the formation of summer smog (kg/kWh)

J – total number of substances contributing to the formation of summer smog

3.2.2.8 Land use and quality

Land is a limited commodity, particularly in countries with relatively high population densities like the UK (which houses around 250 people per square kilometre [144]). Three indicators are included under this category:

- *land occupation,*
- *greenfield land use;* and
- *terrestrial eco-toxicity*.

Land occupation is a measure of the total land occupied throughout the life cycle and the period for which it is unavailable for other use. This reflects the extent to which land is 'locked' for other uses and cannot enhance biodiversity by succession or cultivation. It is calculated as follows:

$$ILU = A \times t \quad (\mathrm{m^2 \cdot yr/kWh}) \qquad (17)$$

ILU – total impact of energy technology on land use over time ($\mathrm{m^2 \cdot yr/kWh}$)
A – land area occupied ($\mathrm{m^2}$)
t – time over which land is occupied (yr)

As shown above, the unit of land occupation is $\mathrm{m^2yr}$, reflecting the fact that land is occupied for many years. For example, considering only the site of the power plant itself, a new nuclear plant would operate for 60 years, then remain on site for several more years during decommissioning (the exact length of time being determined by the owner's decommissioning policy).

Greenfield land use represents the percentage of land converted from a near-natural state relative to the total amount of land used for the construction of a power plant:

$$GF = \frac{GFA}{TLA} \times 100 \quad (\%) \qquad (18)$$

GF – percentage of greenfield land used for construction of power plant (%)
GFA – area of greenfield land used ($\mathrm{m^2}$)
TLA – total land area occupied by the power plant ($\mathrm{m^2}$)

It is a rough proxy for loss of biodiversity. The results of this indicator depend on the sites being proposed for new build. For example, despite all eight of the proposed UK sites for nuclear new build being adjacent to existing power stations, seven of the plots themselves are currently greenfield, including farmland, woodland, drained marsh and a golf course [145].

Neither of the above indicators takes into account toxic emissions to land, which are covered by the life cycle *terrestrial eco-toxicity* indicator, estimated by a method similar to that for marine and freshwater eco-toxicity (see Section 3.2.2.2). The indicator is based on the maximum tolerable concentrations of toxic substances by different organisms in terrestrial environment. The reference substance is 1,4-dichlorobenzene and it is calculates as:

$$TETP = \sum_{j=1}^{J} TETP_j \times B_j \qquad (19)$$

(kg 1,4-DCB eq./kWh)

$TETP$ – terrestrial eco-toxicity potential of energy technology (kg 1,4-DB eq./kWh)
$TETP_j$ – terrestrial eco-toxicity potential of toxic substance *j* (kg 1,4-DB eq./kg)
B_j – emission of substance *j* to land (kg/kWh)
J – total number of toxic substances emitted to land

3.2.3 Social issues and indicators

While techno-economic and environmental indicators for energy systems are relatively well established, social indicators are less well developed. This is mainly due to the complexity and variety of social issues pertinent to energy systems as well as their mainly qualitative and subjective nature. To account for some of the social issues relevant to electricity generation, and particularly nuclear power in the UK [117, 146], the following eight categories of social indicators are proposed within this framework (Table 2):

- provision of employment;
- human health impacts;
- large accident risk;
- local community impacts;
- human rights and corruption;
- energy security;
- nuclear proliferation; and
- intergenerational equity.

The motivation for selecting and developing these indicators is discussed below for each indicator in turn.

3.2.3.1 Provision of employment

Large scale electricity generation has the potential to provide many jobs. For instance, the construction of a single new nuclear reactor provides over 1000 jobs for approximately six years [147] in addition to other jobs in the manufacture of components. It then supports around 500 jobs on-site throughout its operating life of 60 years [147, 148] as well as more, indirect, employment throughout the fuel cycle. In several cases in the UK, areas with aging power stations are heavily reliant on the prospect of new build to replace as many jobs as possible when the current station closes. For instance, Anglesey is working towards realising the Government 'Energy Island' vision, by securing a significant fraction of its total employment in nuclear and renewable energy generation [149].

To account for both direct and indirect employment, two indicators are included in this category: *direct* and *total employment* (Table 2). The former refers to employment created in the life cycle of the power plant, i.e. construction, operation, maintenance and decommissioning. Total employment also includes indirect employment up and down the supply chain as a result of the facility's existence. For power plants, this includes jobs in component manufacturing, fuel mining, fuel processing, waste management and other services to the plant over its lifetime. Indirect employment is not to be confused with induced employment, which is the employment created outside the supply chain as a result of increased disposable income. Induced employment can be estimated using a multiplier so that, for example, 0.25 induced jobs are assumed to result from every one direct or indirect job [as in 63]. However, induced employment is not considered within this framework due to the uncertainties associated with such estimations.

Since the employment provided by a power plant varies greatly by life cycle stage, it is more meaningful and informative to express this indicator in terms of person-years (per total electricity generated) rather than absolute number of jobs (per total electricity generated). For instance, as mentioned above, if 1000 people are employed for six years during the construction of a plant, and 500 people are employed during the operation of the plant over 60 years, then the total employment expressed in person-years is 36,000 [= (1000 × 6) + (500 × 60)]. This should then be divided by the total lifetime electricity output of the plant. The alternative to using person-years as a unit would simply be to sum the number of jobs to 1500 (and divide by electricity output), regardless of the duration of the employment, thus providing only partial information.

Direct and *total employment* are both calculated as follows, with total employment simply including more life cycle stages (as discussed above):

$$DE = \frac{\sum_{i=1}^{I} DE_i \times t_i}{P_{tot}} \quad \text{(person-yrs/GWh)} \quad (20)$$

DE – direct employment provision over the life cycle of an energy technology (person-yrs/GWh)
DE_i – direct employment provision in life cycle stage i (no. of people employed)
t_i – duration of employment in life cycle stage i (yrs)
P_{tot} – total amount of energy generated over the lifetime of energy technology (GWh[7])
I – total number of life cycle stages

3.2.3.2 Human health impacts

Electricity generation incurs many types of human health impacts, ranging from workplace accidents to the more widespread detriments associated with toxic emissions. For instance, the Institute of Occupational Medicine estimates that eliminating all anthropogenic $PM_{2.5}$ emissions would result in gains in life expectancy three or four times higher than those that could be achieved by eliminating all motor traffic accidents or passive smoking [150].

In order to assess human health impacts as fully as possible, the following three indicators are proposed, applicable along the whole life cycle of electricity generation (Table 2):

- worker injuries;
- human toxicity potential (excluding radiation); and
- human health impacts from radiation.

These indicators do not include the effects of large accidents, which are covered by the *accident risk indicator* (see Section 3.2.3.3).

The first indicator is related to worker safety, including contractors and subcontractors, and it measures the number of injuries per unit electricity generated. It includes fatalities, major injuries and minor injuries that cause an absence from work of more than three days (Table 2). Results are calculated by multiplying employment (in person-years) by injury rates for the specific type of work involved at each stage of the life cycle, as follows:

[7] GWh are used rather than kWh to avoid small numbers

$$WI = \sum_{i=1}^{I} E_i \times r_i \quad \text{(injuries/GWh)} \qquad (21)$$

WI – total number of worker injuries (injuries/GWh)
E_i – employment in life cycle stage i (person-yrs/GWh)
r_i – average annual injury rate for the sector appropriate to life cycle stage i (injuries/worker)

Sector-specific injury rates are available from the Health and Safety Executive [151]. For foreign stages of the life cycle occurring outside the UK, the same UK injury rates are used for reasons of consistency. It is acknowledged that rates may differ in other countries, but different national methods of injury rate estimation mean that figures from different countries are rarely comparable.

The type of work involved in a technology's life cycles plays a great role in determining the number of worker injuries it causes. For instance, life cycles that involve more mining (either of fuel or materials) will generally cause more worker injuries due to the higher injury rates seen in the mining sector (average 2008-2010 injury rate in the UK of 1117 injuries per 100,000 workers, compared to 777 for construction, 772 for manufacturing and 356 for fuel fabrication [151]).

Human toxicity potential expresses the potential harm to humans from toxic substances emitted in the life cycle of energy generation. It excludes impacts from radiation, which are accounted for by the indicator discussed below. Similarly to the environmental eco-toxicity potentials discussed in Section 3.2.2, it is calculated according to the CML methodology [152] and expressed in dichlorobenzene equivalents per kWh. It takes into account toxic releases to air, water and soil:

$$HTP = \sum_{j}^{J} HCA_{Aj} \times B_{Aj} + \sum_{j}^{J} HCW_{Wj} \times B_{Wj} + \sum_{j}^{J} HCS_{Sj} \times B_{Sj} \quad \text{(kg 1,4-DCB eq./kWh)} \qquad (22)$$

HTP_{Aj}, HTP_{Wj}, and HTP_{Sj} – toxicological potentials for substances emitted to air, water and soil, respectively (kg 1,4 DCB eq./kg)
B_{Aj}, B_{Wj} and B_{Sj} – emissions of different toxic substances into the three environmental media (kg/kWh)
J – total number of substances toxic to humans

Finally, *human health impacts from radiation* are measured. They are expressed in terms of disability-adjusted life years (DALY), in line with the World Health Organisation's 'burden of disease' measurements [153]. DALYs include the years of life lost due to cancer and hereditary disease as well as the years in which individuals live with disease/disability. The severity of each disease is based on evaluations by a panel of health experts using a scale from 0-1, where '0' is perfect health and '1' is death. The indicator is calculated as follows:

$$HIR = \frac{\sum_{d}^{D} YL_d + D_d S_d}{P_{tot}} \quad \text{(DALY/GWh)} \qquad (23)$$

HIR – human health impacts from radiation (DALY/GWh)

YL_d –life lost due to disease d (yr)

D_d – average duration of disease d (yr)

S_d – average severity of disease d, as estimated by health experts (0-1)

P_{tot} – total amount of energy generated over the lifetime of energy technology (GWh)

3.2.3.3 Large accident risk

The risk of a large accident is a critical issue in the energy sector, and its minimisation is particularly important for public acceptance. The large accident risk indicator measures the expected number of fatalities due to large accidents over the life cycle of electricity generation and is expressed per unit of electricity generated (Table 2):

$$LAR = \sum_{i}^{I} LAR_i \quad \text{(fatalities/GWh)} \qquad (24)$$

LAR – total number of fatalities (fatalities/GWh)

LAR_i – number of worker fatalities in life cycle stage i per GWh electricity produced (no./GWh)

I – total number of life cycle stages

3.2.3.4 Local community impacts

This category aims to assess the impacts of a power station on its local community (see Table 2). Some of the possible impacts include provision of employment to local communities as well as contribution to their development and welfare. Therefore, the following three indicators are proposed under this category:

- *proportion of staff hired from local community;*
- *proportion of spending on local suppliers*; and
- *direct investment in local community*.

Similar indicators have been suggested by several other authors [see, for example, 44, 64, 66].

Proportion of staff hired from local community is expressed relative to the total provision of direct employment during the operation stage of a power plant. It is calculated as follows:

$$P_{LS} = \frac{LS}{DEO} \times 100 \quad (\%) \qquad (25)$$

P_{LS} – proportion of staff hired from local community during the operation stage of a power plant (%)
LS – number of staff hired from local community per unit of electricity generated during the operational lifetime of a power plant (person-yrs/GWh)
DEO – total number of staff directly employed per unit of electricity generated during the operational lifetime of a power plant (person-yrs/GWh)

Proportion of spending on local suppliers measures the percentage of spending in the local community and is expressed relative to the total expenditure each year:

$$P_{LSUP} = \frac{S_{LSUP}}{S_{tot}} \times 100 \quad (\%) \qquad (26)$$

P_{LSUP} – proportion of spending on local suppliers each year (%)
S_{LSUP} – annual spend on local suppliers (£/yr)
S_{tot} – total annual expenditure related to the operation and maintenance of the plant (£/yr)

Finally, *direct investment in local community* aims to promote equitable distribution of wealth through direct returns to the local community [64]. This includes investments in local schools, hospitals, infrastructure, environmental projects etc. This indicator is expressed as the percentage invested relative to total company revenue:

$$P_{LDI} = \frac{LDI}{R_{tot}} \times 100 \quad (\%) \qquad (27)$$

P_{LDI} – proportion of direct investment in local community each year (%)

LDI – annual investment in local community (£/yr)

R_{tot} – total annual revenue (£/yr)

Ideally, these indicators should span the construction, operation and decommissioning stages, but it is unlikely that information on all three stages will be available at the same time; data for construction and decommissioning may not be available at all. Besides, different companies may be involved in these three life cycle stages making it even more difficult to obtain meaningful information. Therefore, it is suggested that these indicators only cover the operation stage of a power plant. Furthermore, given that these indicators are company- rather than technology-specific, they can only be used by individual companies with specific knowledge of their impact on, and contribution to, local communities. Alternatively, it may be possible to use industry average data, but this would incur further data collection problems and would contribute little to distinguishing between different technologies.

3.2.3.5 Human rights and corruption

Ethical problems surrounding human rights and corruption are a major concern in some countries where the social and regulatory regimes are lax. However, it is difficult to assess this indicator in an unbiased fashion since evidence of rights violations and corruption is not always available and often ambiguous: value judgements are inherent in the definition of terms like 'violation' and 'corruption'. For this reason, a simplified indicator is proposed based on the Corruption Perceptions Index (CPI) developed by Transparency International [154]. The CPI scores countries on a scale from 0-10 based on the level of corruption of their politicians and official administration, whereby 0 means extremely corrupt and 10 means completely clean. For example, Denmark, New Zealand and Singapore top the league with a score of 9.3 while Somalia is at the bottom with a CPI of 1.1. Although CPI admittedly only considers corruption and not human rights violations, it is arguably a reasonable proxy, as public corruption and human rights issues are often closely correlated.

Within this framework, it is proposed to calculate the human rights and corruption indicator as an average CPI of the countries involved in the life cycle of an energy system (see below). For instance, if a nuclear fuel cycle involved uranium mining in Namibia (CPI = 4.4), conversion, enrichment and fuel fabrication in Germany (CPI = 7.9) and waste storage and disposal in the UK (CPI = 7.6), the average CPI for this life cycle would be 6.6.

$$CPI = \frac{\sum_{c}^{C} CPI_c}{C} \quad \text{(Score 0-10)} \qquad (28)$$

CPI – average corruption perceptions index (Score 0-10)
CPI_c – corruption perceptions index for country c in the life cycle of an energy technology
C – total number of countries

As is the case with the local community indicators discussed in Section 3.2.3.4, human rights and corruption will depend mainly on company sourcing policy rather than on energy technology, although inevitably the technology may dictate where the fuels and raw materials are sourced from.

3.2.3.6 Energy security

Energy security is clearly one of the main objectives of UK energy policy [111, 117]. The UK currently relies on coal and gas for around 75% of its electricity [16], both of which are finite resources and require substantial imports, reducing the UK's energy security.

Previously, energy security has been assessed by estimating the amount of imported fossil fuel avoided by non-fossil fuel generation technologies [43], calculating global fuel availability [35, 40, 45] or via qualitative assessment [36, 37, 39]. Here, three different but related indicators are used to assess the level of energy security associated with different electricity options (Table 2):

- *amount of imported fossil fuel potentially avoided* (adopted from [43]);
- *diversity of fuel supply*; and
- *fuel storage capability*.

The indicator *imported fossil fuel potentially avoided* applies only to the operational stage and is expressed in terms of the amount of fossil fuel that would have to be burned to provide the equivalent electrical output of a non-fossil source, using the current fossil fuel fleet as a benchmark, as follows:

$$IFA = \frac{100}{\eta_a} \times K \quad \text{(koe/kWh)} \qquad (29)$$

IFA – imported fossil fuel potentially avoided (koe/kWh)

η_a – average efficiency of the fossil fuel fleet (%)

K – conversion for kilowatt-hour to kilograms oil equivalent (koe/kWh)

The installed capacity of fossil fuel stations (gas, coal and oil) in the UK and their average efficiencies [155] allow calculation of the overall conversion efficiency of the fossil fuel fleet, which is approximately 43%. Therefore, producing 1 kWh of electricity from that fleet requires around 0.2 kilograms of oil-equivalent[8]. Thus, this amount of fossil fuels would be avoided by using non-fossil fuel electricity technologies. It should be noted that, since the UK produces some oil, coal and gas indigenously, not all of this amount would necessarily be imported. However, given that the UK is currently a net importer of all three of those fuels [16], it is reasonable to assume that a reduction in demand equates to a reduced need to import. In reality, a reduction in fossil fuel demand might simply mean that import levels are maintained while more indigenously produced fuels are exported.

In addition, a simple, novel indicator is proposed for the first time to address *diversity of fuel supply mix.* It is based on Simpson's Index of Diversity (SID) [157, 158] and expressed as a score on a scale from 0-1. This indicator applies to the operational stage (see Table 2) and takes into account the proportions of national fuel demand supplied domestically and imported, corrected for SID, as follows:

$$DFS = P_{in} + P_{im}\left(1 - \frac{\sum_{c}^{C} n_c(n_c - 1)}{9900}\right) \qquad (30)$$

(Score 0-1)

DFS – diversity of fuel supply mix

P_{in} – proportion of national fuel demand produced indigenously

P_{im} – proportion of national fuel demand imported

n_c – percentage of fuel imports supplied by exporting country c

In ecological studies, SID is used to quantify the biodiversity of a habitat by taking into account the number of species present (richness) as well as the relative abundance of each species

[8] 1 kWh = 8.60×10^{-5} toe [156]. At conversion efficiency of 43%, production of 1 kWh requires ((100 ÷ 43) × 8.60×10^{-5}) = 2×10^{-4} toe = 0.2 koe.

(evenness). Here, SID is applied to the import mix of the fuel in question. The SID of the import mix is then multiplied by the proportion of the fuel that is imported, which in turn is added to the proportion produced indigenously. In this way, the overall result of the indicator increases in situations where a greater proportion of fuel is produced indigenously; or the same proportion of fuel is imported from a greater number of exporters; or the import mix is split more evenly between exporters. Cases in which fuel supplies depend heavily on one exporter will therefore score badly as security of supply is too vulnerable.

Finally, *fuel storage capability* is quantified as the energy density of the fuel and applies to two life cycle stages: fuel fabrication and operation (Table 2). This indicator can be expressed either in terms of energy content per mass or volume of fuel and provides information on the ease of storage of different types of fuels. For conventional fuels, it is simply the net calorific value of the fuel (GJ/m^3). In the case of nuclear power, the relevant criterion is the energy density per unit volume of a fuel assembly rather than per unit volume of uranium. This can be calculated as:

$$ED = \frac{MA_u \times BU}{VA_{tot}} \quad \text{(GJ/m}^3\text{)} \qquad (31)$$

ED – volumetric energy density of nuclear fuel (GJ/m^3)

MA_u – mass of uranium in one fuel assembly (t)

BU – assumed ‘burn-up’ of uranium in fuel (GJ/tU)

VA_{tot} – total volume of one fuel assembly (t)

Renewables (apart from biomass) do not require fuel, and are therefore not subject to supply disruptions (although they may produce energy intermittently). As a result, their fuel storage capability is assumed to be infinite.

3.2.3.7 Nuclear proliferation

Based on the objectives of the Treaty for Non-Proliferation of Nuclear Weapons (NPT) [159], nuclear proliferation can be defined as the spread of nuclear weapons and weapons technology. In recent years the phrase has also become associated with the potential targeting of civil nuclear facilities by terrorist groups, although this is a separate issue. The UK, as a nuclear power, has already ‘proliferated’ and subsequently signed the NPT. Consequently, non-proliferation objectives must be considered from a different perspective. For instance, several measures of proliferation resistance use the existence or non-existence of safeguards in the country of operation as a criterion [160, 161]. This is not informative in this framework because of the focus on the UK which signed the NPT in 1968 [162]. Similarly, while the NPT aims for nuclear disarmament, the existence of civil nuclear reactors in the UK is of no direct relevance to the reduction in number of the UK's approximately 200 nuclear warheads [163], as this would be dictated solely by defence policy. There are, however, three main factors which are simultaneously of concern from a proliferation perspective and of relevance to energy systems:

i) the ease by which nuclear weapons material might be produced from power reactors;
ii) the ease by which nuclear weapons material might be obtained from the chosen fuel cycle; and
iii) the effect of possessing certain technologies on global non-proliferation efforts.

The first criterion addresses the fact that certain reactors provide weapons-usable plutonium more readily than others. CANDU and Magnox, for example, do not require enriched fuel, circumventing the need for enrichment facilities. CANDU reactors also allow fuel unloading while still online, making extraction of low burn-up spent fuel easier (although this would require operation outside of safeguards).

The second criterion addresses the products of the fuel cycle: reprocessing involves the separation of uranium and/or plutonium from spent fuel, leading to various risks such as theft and detonation (discussion of which, in relation to the UK plutonium stockpile, can be found in [164]). Indeed, plutonium production (in terms of weapons-usability, mass produced and ease of appropriation) is the usual focus of nuclear proliferation resistance indicators [see, for example, 165, 166, 167]. However, these indicators are often over-complicated, requiring large amounts of data that are not freely available. Moreover, detailed assessment of plutonium alone seems increasingly redundant given the fact that almost any grade of plutonium, including that extracted by so-called proliferation-resistant reprocessing techniques (such as COEX, UREX and THOREX[9]), could be used to create a nuclear weapon with relative ease, albeit a potentially low-yield one [165].

Regarding the third criterion, if enrichment technology, for instance, is seen as a requirement for civil nuclear power, it is diplomatically and politically difficult for a possessor of that technology to deny it to a country that does not possess it. This is echoed by the public concern expressed in response to the 2006 UK energy White Paper [117]: many respondents stated that possessing

[9] COEX: co-extraction (of uranium and plutonium); UREX: uranium extraction; THOREX: thorium extraction

nuclear power in the UK was undesirable because it encouraged other countries to pursue nuclear technology in general.

Considering these three concepts, it is suggested that the nuclear proliferation indicator be based on the following considerations (Table 2):

1. use of non-enriched uranium in a reactor capable of online refuelling, such as CANDU;
2. use of reprocessing; and
3. requirement for enriched uranium.

It spans the whole life cycle of nuclear power. It is expressed as a score on a scale from 0-3 with all three criteria equally weighted; a lower score is preferred. To capture all three criteria, the enrichment, operation, reprocessing and MOX fabrication stages of the life cycle must be considered. Therefore, a PWR in a reprocessing fuel cycle would score 2 because PWRs require enriched fuel (indirectly promoting the spread of enrichment technology) and, in this case, involve reprocessing (leading to risks of theft and weapons manufacture). While this is acknowledged to be a simplistic evaluation, it is thought to be sufficient for consideration of current nuclear options for the UK. It is not, however, appropriate or sufficiently detailed for application to future (Generation IV) nuclear technologies.

3.2.3.8 Intergenerational equity

Maintaining resources for future generations is a notion at the centre of sustainable development. Unfortunately the nature of these ‘resources’ is extremely hard to define in a universally acceptable manner, being open to interpretation depending on the substitutability of different forms of capital[10]. Moreover, the timescales involved are highly debatable, although they are certainly long enough to provide exceptionally low certainty about future contexts and conditions. These issues, along with four different models[11] of intergenerational equity, are discussed in more detail by Brown Weiss [168]. As a result of these difficulties, intergenerational

[10] ‘Capital’ here refers to any assets of value, including financial wealth, environmental resources and knowledge. For instance, the effects of environmental degradation on future generations can be argued to be offset by accumulated wealth and technical progress (see below).

[11] In the ‘preservationist model’, environmental quality is preserved intact for future generations. In the ‘opulence model’, wealth and knowledge are accumulated and assumed to substitute natural capital. In the ‘technology model’, improved technological abilities are assumed to fully compensate for loss of natural capital. In the ‘environmental economics model’, proper costing of externalities accounts for any effects of our activities on future generations [168].

equity is rarely considered in sustainability assessments. Nevertheless, it is crucial that it be included.

In the context of electricity generation, there are three main issues related to intergenerational equity that should be considered: *climate change, abiotic resource depletion* and *long-lived hazardous waste*. Of these, only the latter two are considered here. *Abiotic resource depletion* applies to the whole life cycle, whereas *long-lived hazardous waste* is only relevant to the waste disposal stage of the life cycle (Table 2). Regarding climate change, one must differentiate between global warming (as a result of life cycle GHG emissions, as discussed in Section 3.2.2.3) and climate change itself (a complex phenomenon of which average global warming is only a part [see 169]). In the context of energy policy in the UK and elsewhere, GWP is used as a proxy for climate change, so this approach is also followed within this framework. Since GWP is normally considered an environmental problem and estimated using LCA, it is included within this framework under the environmental indicators (see Section 3.2.2.3). Thus, to avoid double counting, it is not considered again as part of the intergenerational equity category.

The *depletion of abiotic resources* indicator comprises depletion of minerals and fossil fuels, and is quantified using the CML methodology [49]. It is split into two indicators to allow for the fact that fossil fuels, as energy vectors, are essentially substitutable, whereas elements and the substances containing them perform very different functions and are not often interchangeable [49]. The fossil fuel depletion indicator is expressed in MJ/kWh. The elements indicator takes into account the reserve sizes and usage rates of different resources by normalising to antimony (since this is not a widely used metal and therefore has a relatively constant reserve lifetime):

$$ADP_F = \sum_j^J ADP_{Fj} \times B_{Fj} \qquad (32)$$

(MJ/kWh)

ADP_F – abiotic resource depletion potential for fossil fuels (MJ/kWh)

ADP_{Fj} – abiotic depletion potential for fossil fuel j (MJ/kg)

B_{Fj} – quantity of fossil fuel j used (kg/kWh)

$$ADP_M = \sum_j^J ADP_{Mj} \times B_{Mj} \qquad (33)$$

(kg Sb eq./kWh)

ADP_M – abiotic resource depletion potential for minerals (kg Sb eq./kWh)

ADP_{Mj} – abiotic depletion potential for mineral j (kg Sb eq./kg)

B_{Mj} – quantity of mineral j used (kg/kWh)

The *long-term storage of hazardous waste* indicator addresses two types of waste: radioactive waste from nuclear power and CO_2 captured from fossil (and biomass) fuel technologies. Both types of waste have obvious consequences for future generations due to the possibility of accidental leaks and the burden of monitoring for long time periods. The risk of accidental leaks cannot be quantified sufficiently at this stage due to the lack of operating repository experience and site-specific information as well as the difficulties in establishing an agreed timeframe. The long-term monitoring burden, however, can be expressed by using the volume of waste (or the volume of its storage facility) that requires monitoring as a rough proxy. It should be noted that this approach cannot address any activity that must occur between production of the waste and final disposal when long-term monitoring begins. This is particularly relevant for spent nuclear fuel as it requires a period of several decades to cool down before it is suitable for disposal, the duration of which varies depending on burn-up: the NDA estimates that spent fuel from an Areva EPR with a burn-up of 50 GWd/tU would need to be cooled for 75 years before disposal, rising to 100 years for spent fuel with a burn-up of 65 GWd/tU [170].

Nuclear waste is normally expressed volumetrically, whereas CO_2 is normally expressed in mass terms and therefore requires conversion to storage volume as described below.

$$LSW_{NUC} = \sum_{i}^{I} w_i \quad (\mathrm{m^3/kWh})$$

LSW_{NUC} – Long-term storage of packaged nuclear waste (m^3/kWh)
w_i – quantity of packaged nuclear waste destined for geological disposal produced in life cycle stage i (m^3/kWh)

$$LSW_{CAR} = \frac{\sum_{i}^{I} c_i}{d} \quad (\mathrm{m^3/kWh})$$

LSW_{CAR} – Long-term storage of supercritical carbon dioxide from CCS (m^3/kWh)
c_i – quantity of carbon dioxide removed for long-term storage in life cycle stage i (kg/kWh)
d – density of carbon dioxide under supercritical conditions at storage site (kg/m^3)

It should be noted that the life cycles of technologies other than nuclear power and CCS also create a long-term waste management burden in the form of non-radioactive hazardous wastes. Ideally these wastes should also be accounted for within this indicator. However, hazardous wastes are diverse and a lack of comprehensive data on their production and treatment throughout the life cycle precludes their inclusion. Moreover, while most industrial processes produce hazardous waste, nuclear waste and CO_2 for underground storage are unique to their respective technologies and therefore create an additional future burden.

3.3 Summary

The sustainability assessment framework described in this chapter constitutes the main deliverable of this research project. The framework uses a life cycle approach, taking into account techno-economic, environmental and social sustainability issues from ‘cradle to grave’. It draws on the work of other authors (as discussed in the previous chapter) and also on collaboration with stakeholders including industry, Government, NGOs and experts from academia. As a result, it arguably addresses a comprehensive range of stakeholder concerns.

By taking a life cycle approach, the framework ensures that different electricity options can be considered on an equivalent basis, as well as allowing the identification of ‘hot spots’ in the life cycle that may act as focal points for criticism or improvement.

The proposed methodological framework, outlined in Figure 2, involves the following main steps:

v. definition of the goal and scope of the sustainability assessment;
vi. selection of the electricity options and identification of possible future electricity scenarios to be assessed;
vii. identification of relevant sustainability issues and definition of related sustainability indicators to enable the assessment; and
viii. assessment of techno-economic, environmental and social sustainability along the life cycle of the electricity options.

The main novelty of the framework is in the set of 42 life cycle sustainability indicators that are proposed, addressing six techno-economic, eight environmental and eight social issues. These have been described throughout this chapter, are summarised in Table 2 and were published in [31]. The proposed indicators draw on some of the previous approaches to sustainability assessment discussed in the literature review in Chapter 2 [such as 32-35, 40, 44, 45, 46, 57, 64, 78, 91] as well as on direct stakeholder input.

The following chapters discuss the application of the sustainability indicators to electricity options relevant to the UK. These case studies demonstrate the framework and provide information that, it is hoped, will assist policy- and decision-makers.

4 Nuclear power

In this chapter, the sustainability assessment framework is applied to nuclear power. As the aim is to assess the sustainability of potential new build in the UK, the focus is on pressurised water reactors (PWRs). The chapter starts in Section 4.1 with an overview of the current situation with respect to nuclear power in the UK. This is followed by a summary of the nuclear life cycle and its related sustainability issues in Section 4.2. Section 4.3 then describes the data sources and assumptions that were used to assess nuclear power, while Section 4.4 presents and discusses the results. Finally, Section 4.5 summarises the data quality analysis of this assessment.

4.1 Nuclear power in the UK: the current situation

The UK was a pioneer of nuclear power, operating the first grid-connected reactor in the world, Calder Hall 1, from 1956 [171]. This was the first of 26 indigenously designed Magnox-type[12] reactors eventually built in the UK, of which two are still operating (both at Wylfa; see Table 4). The advanced gas-cooled reactor (AGR)[13], also designed indigenously, was then built from the 1970s, with many examples still in operation at the time of writing (Table 4). Following significant cost overruns with AGRs, nuclear deployment slowed until the last reactor to be built, a pressurised water reactor (PWR) at Sizewell B, came online in 1995: it is expected to operate until at least 2035.

The current UK nuclear fleet has an installed capacity of around 10 GW, which typically provides about 15-17% of national electricity supply [5]. All reactors are positioned on the coast in order to exploit the sea for direct cooling [8]. Since the Government's publication of the 2006 energy review [172], the construction of new nuclear power stations has been part of policy, as exemplified in the recent National Policy Statement for Nuclear Power Generation [17]: "*Given the urgent need to decarbonise our electricity supply and enhance the UK's energy security and diversity of supply, the Government believes that new nuclear power stations need to be developed significantly earlier than the end of 2025*". This policy stance has encouraged new plant proposals and site assessments. As of mid-2011, National Grid had agreed 16.7 GW of

[12] Magnox is a Generation I reactor design. The name is derived from the magnesium alloy used in the fuel cladding: 'MAGnesium Non-OXidising'. It uses natural (un-enriched) uranium metal as fuel with graphite as moderator and CO_2 as coolant.
[13] AGR is a Generation II reactor design using enriched uranium in ceramic uranium oxide as fuel with, like Magnox, graphite as moderator and CO_2 as coolant.

potential new grid connections at eight[14] sites in the UK by 2025 [17]. Utility companies currently have 19 GW of new nuclear capacity planned or proposed in the UK [8].

However, following the tsunami-related accident at the Japanese Fukushima Daiichi nuclear plant in March 2011, these new proposals have become less certain. Initial concerns over safety and policy in the UK were addressed by the Weightman report [22], but decisions overseas have since affected the UK outlook: for instance, Horizon Nuclear Power (a joint venture between German utilities RWE and EOn) announced their withdrawal from nuclear proposals in March 2012 citing their weakened financial position following the Fukushima-inspired phase-out of nuclear plants in Germany [174]. Nevertheless, their proposals may be continued by new owners, and similar proposals by other companies still stand: EDF Energy, for example, still has over 6.5 GW planned [8].

Table 4: Nuclear plants currently operating in the UK [8]

Power Station	Type	Net MWe	Commercial operation	Expected closure date
Wylfa, Anglesey	Magnox	980	1971	2012-2014
Hinkley Point B, Somerset	AGR	860	1976	2016
Hunterston B, North Ayrshire	AGR	840	1976	2016
Dungeness B, Kent	AGR	1090	1983	2018
Hartlepool, Hartlepool	AGR	1190	1983	2019*
Heysham 1, Lancashire	AGR	1160	1983	2019*
Heysham 2, Lancashire	AGR	1230	1988	2023
Torness, East Lothian	AGR	1250	1988	2023
Sizewell B, Suffolk	PWR	1188	1995	2035

*Originally expected to close in 2014 but recently extended by five years by operator EDF Energy [175].

[14] Originally, 11 sites were proposed, but the government subsequently ruled out three [173].

4.2 Nuclear life cycle and sustainability issues: an overview

The life cycle of nuclear power is depicted in Figure 4. As shown, it encompasses uranium mining, enrichment and fuel production; construction, operation and decommissioning of the plant; and waste management.

The UK does not have indigenous uranium reserves, so all fuel is imported. Globally, mining of uranium currently takes place in 18 countries, with Kazakhstan, Canada and Australia providing over 60% of total mined uranium supply [176]. Uranium can therefore be imported into the UK from any of these countries, also 'importing' the related sustainability impacts. These include issues such as leaching of toxic substances, worker health and safety, distribution of revenues, local community benefits and indigenous peoples' rights; more detail on the sustainability issues specifically associated with mining are found in, for example, Azapagic [64] and GRI [177]. It should be noted that approximately 13% of global uranium supply is currently derived from diluted military material rather than from primary repositories [178]. This is an illustration of the link between civil nuclear fuel and nuclear weapons: each can be created from the other. This raises questions related to nuclear weapons proliferation, as discussed in Section 3.2.3.7.

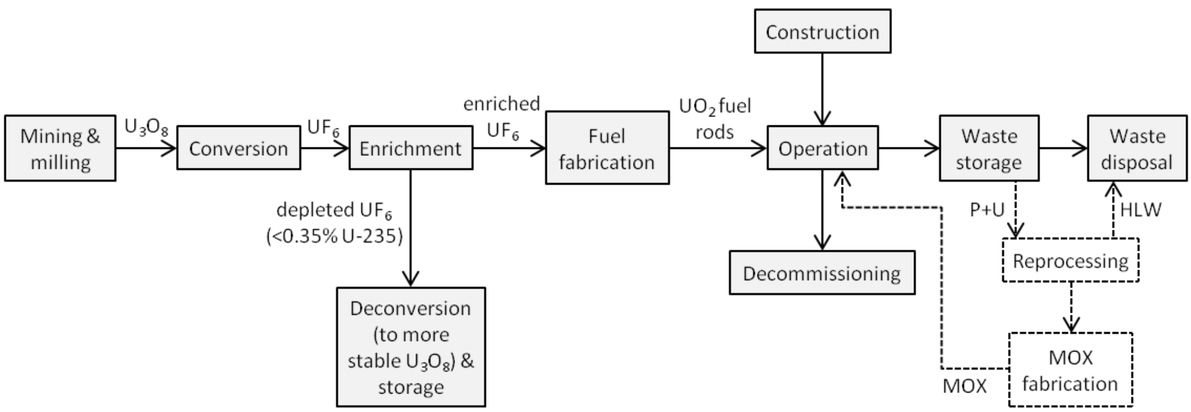


Figure 4: The life cycle of nuclear power (HLW: high level waste; MOX: mixed oxide fuel; the broken line indicates optional parts of the life cycle)

Imported uranium is then converted into uranium hexafluoride before being enriched and finally converted into fuel. For a modern PWR, uranium is typically enriched to around 4-5%[15] U-235 via either gaseous diffusion or centrifuge technology (although diffusion is being phased out due to

[15] Other designs, such as Magnox or CANDU, can run on natural (non-enriched) uranium, which is 0.7% U-235 [179]. These designs are not proposed for new build.

its much lower efficiency) [179]. Fuel fabrication then involves the production of uranium dioxide pellets which are loaded into zirconium alloy rods to provide structural support [180]. These rods are then arranged into a fuel assembly for insertion into a reactor. Most of this activity takes place in the UK, although some processes currently take place elsewhere. For example, fuel for Sizewell B is currently manufactured in two stages taking place in Russia and Germany, rather than in the UK's own Springfields fuel fabrication site [181, 182]. Similar sustainability issues that might be of concern to any other industrial process also apply to this part of the fuel life cycle, including environmental and social impacts (see Table 2).

Construction and operation of a nuclear power plant can take 5-10 and 40-60 years, respectively. Specific issues of relevance to these stages include public concern that investment in nuclear power could divert investment away from renewables [183] along with lingering doubts over the safety of nuclear reactors. However, it is clear that the key determinants of UK policy are climate change and energy security [111, 117, 172, 184] and these form the prime strategic concerns of new power plants.

The end of the nuclear life cycle – plant decommissioning, waste storage and disposal – is arguably the most contentious issue for nuclear power. No country currently has a final repository for spent fuel and high-level nuclear waste (HLW), although plans in the UK have progressed in recent years following the reports of the Committee on Radioactive Waste Management (CORWM) [185]. Moreover, the UK's Drigg facility for low-level waste (LLW) storage is currently thought to be almost full, although a new LLW storage vault and separate recycling facility should help to alleviate this problem [186, 187].

As mentioned previously, another issue specific to nuclear waste is the potential for nuclear proliferation. In the context of civil nuclear power in the UK, this is affected by factors such as reactor design and choice of fuel cycle. For instance, while it is increasingly acknowledged that all reactor-grade plutonium is weapons usable, the safety, predictability and yield are improved if the fuel is withdrawn early (at low burn-up) [165, 166]. This is easier to achieve with a CANDU (Canadian Deuterium Uranium) reactor than with a PWR (pressurised water reactor) or BWR (boiling water reactor) due to its ability to refuel whilst online, in addition to the fact that it does not require enrichment facilities [188]. However, arguably, its lack of enrichment requirements can also reduce proliferation risks by negating the perceived need for enrichment technology in prospective nuclear nations.

As shown in Figure 4, spent fuel can be reprocessed into mixed oxide fuel (MOX)[16] to reduce the amount of nuclear waste generated and increase the energy recovered from the original nuclear fuel by up to 30% [190]. MOX can also be manufactured from ex-military plutonium, providing a way of reducing weapons-usable stockpiles [see, for example, 191]. In the UK, reprocessing is carried out at the THORP facility and MOX was manufactured at the Sellafield MOX Plant until its closure in 2011 [192]. However, MOX has not been used in Sizewell B [193] and the government currently recommends that any nuclear power stations that might be built in the UK should proceed on the basis that spent fuel will not be reprocessed [111]. Despite this, both reactor designs that have undergone the Generic Design Assessment (GDA)[17] prescribed by the Health and Safety Executive (HSE) are able to use MOX fuel [195, 196]. As such, the possibility of future reprocessing of used fuel and the manufacture of MOX for UK use cannot be ruled out. If spent fuel was reprocessed, the total amount of waste would decrease but plutonium separation may raise nuclear proliferation concerns under certain technical scenarios (especially those using PUREX[18]).

Various sustainability issues associated with different parts of the nuclear fuel cycle are discussed further in the following sections, in conjunction with the related indicators. As previously mentioned, the focus is on PWRs as the technology of choice for potential new build in the UK. The indicators are, where possible, expressed per kWh electricity generated in order to enable equivalent comparisons between nuclear and other electricity options.

4.3 Data sources and assumptions

The key assumptions and data sources for the nuclear option are discussed below. Full results of the sustainability assessment are given in Appendix 3. Wherever possible and available, a range of values for each option has been considered to establish the lower and upper bounds. Where appropriate, average values are used in the sustainability assessment. In other cases, 'central' estimates are used instead, representing the most likely values for present and near-term new

[16] MOX comprises approximately 3-10% plutonium dioxide (depending on the proportion of the Pu-239 isotope) with the remaining 90-97% being depleted uranium dioxide [189]. The resulting fuel behaves in a similar, but not identical, manner to normal, low-enriched, uranium dioxide fuel.
[17] GDA is the regulatory (HSE) procedure by which new reactor designs are approved for use in the UK, pending site-specific licensing [194]. The designs that have undergone GDA are the AREVA EPR and the Westinghouse AP1000 [194].
[18] Plutonium-Uranium Extraction (PUREX) is the current standard method of reprocessing, in which uranium and plutonium are extracted independently.

build, based on the specific technology type expected to be deployed. For instance, the five-year average capacity factor of nuclear plants in the UK is 63.2%, but this is an unrealistically low estimate for new build because most current plants are older advanced gas-cooled reactors (AGRs). Since new plants will be PWRs, a higher capacity factor of 85% is assumed based on industry expectation and the performance of Sizewell B (see Section 4.3.1.1).

4.3.1 Techno-economic data and assumptions

The indicators used for the techno-economic assessment are shown in Table 2. The data sources used are discussed below.

4.3.1.1 Operability

Capacity factor

New nuclear reactors in the UK will be PWRs, whereas the current fleet is dominated by older AGR designs. The UK's only current PWR, Sizewell B, has a significantly higher average capacity factor than the UK fleet average (83.9% lifetime average [197] versus 63.2% five year average [16]). New reactors, also being PWRs, are expected to behave similarly to Sizewell B. As a result, an industry standard figure of 85% is taken as the central estimate. The lower bound is the worst figure reported for the UK from 2005 to 2009 [16], while the higher bound is the achievable value expected for new build.

Availability factor

These figures are based on operational data obtained from the IAEA [197], with the lower bound being the lifetime availability factor of the UK's worst performer (Dungeness B1, 50.67%) and the central estimate being the lifetime performance of Sizewell B (89.2%). The upper bound is a calculation of the maximum achievable value assuming an 18 month refuelling cycle followed by a 40 day outage for refuelling and maintenance.

Technical and economic dispatchability

Dispatchability is the ability of a generating unit to increase or decrease generation, or to be brought on line or shut down as needed [31]. Technical dispatchability comprises four criteria: ramp-up and ramp-down rates as well as minimum up and down times (see Section 3.2.1.1). The overall technical dispatchability score for a technology is obtained by summing up its ranking in each of the four criteria. The data for technical dispatchability of nuclear power have been obtained by observing operator-specified information [95] over a period of several months; they are summarised in Table 5. It should be noted that these figures may reflect the way in which operators choose to run their plants rather than the plants' technical abilities.

The data for economic dispatchability, estimated as a ratio of capital and total levelised costs, are based on the cost estimates described further below.

Table 5: Summary of technical dispatchability data for nuclear power retrieved from Balancing Mechanism Reporting System [95]

Ramp-up rate (%/min.)	worst	0.17
	average	0.17
	best	3.75
Ramp-down rate (%/min.)	worst	0.83
	average	0.83
	best	3.75
Minimum down-time (mins)	worst	999
	average	999
	best	999
Minimum up-time (mins)	worst	999
	average	999
	best	999

<u>Lifetime of fuel reserves</u>

The central estimate for the lifetime of fuel reserves reflects economically recoverable resources, as specified by NEA [100]. The lower estimate assumes that economically recoverable reserves stay the same, but demand increases at the rate suggested by the WNA's high nuclear growth scenario [198], resulting in faster use of reserves. The upper estimate reflects the total available resource including uranium from phosphates [45].

4.3.1.2 Technological lock-in resistance

<u>Ratio of plant flexibility and operational lifetime</u>

Flexibility reflects the ability of each technology to provide trigeneration, net negative CO_2 emissions and high temperature (800°C) H_2 production. Ten points are accrued for each of the three criteria, with the sum being squared and divided by operational lifetime, as shown in Table 6 for nuclear power.

Table 6: Data on the technological lock-in resistance of nuclear power

Tri-generation	yes
Net negative CO_2 emissions	no
Thermochemical H_2 production	no
Lock-in index score (0-30)	10
Lifetime (yrs)	60
Total score (f^2/l)	**1.67**

4.3.1.3 Immediacy

<u>Time to plant start-up</u>

The central estimate for this indicators is taken as the average construction time of nuclear power stations included in 2005 IEA Projected Costs of Generating Electricity report [113]. The lower estimate is based on construction schedules for Westinghouse AP1000 reactors currently being built in China [199], as these are likely to have swift build rates (around five and a half years). The high estimate is the current estimated completion time for the world's first Areva EPR, in Olkiluoto, Finland [200]. As this indicator measures time taken to start up the plant from the start of construction, the figures do not include planning and preliminary studies.

4.3.1.4 Levelised cost of generation

<u>Capital, operational, fuel and total levelised costs</u>

Cost estimates considered here are based on those by Mott MacDonald [201] at 10% discount rate. This source has been selected because it is tailored to the UK case and is relatively recent. The cost estimates in this study therefore inherit most of the assumptions made by Mott MacDonald, such as plant lifespan and average capacity factor. However, these assumptions are broadly in line with those used in the rest of the assessment in this study. Any subsidies are excluded from these costs, including the carbon price applied by Mott MacDonald and the Renewables Obligation Order [12]; subsidies are considered separately in Sections 4.3.1.6 and 4.4.1.6. The cost data are summarised in Appendix 3. The values used in this study have been verified against earlier UK cost estimates [118, 202] as well as data for other OECD countries published by IEA [99, 113] and MIT [119]. However, these data are not included here as they have been found to agree broadly on the relative costs of each electricity option, but not on the absolute costs. The reasons for this are two-fold: firstly, the costs of electricity generation from all technologies have increased greatly in the last few years [201], making older studies obsolete, and secondly, costs (particularly capital) tend to be much lower in some OECD countries, such as

South Korea, than in the UK; this phenomenon reduces average capital costs derived from studies of OECD countries to a point that is not realistic for the UK.

4.3.1.5 Cost variability

Fuel price sensitivity

This indicator has been estimated using the fuel cost data and total levelised generation costs discussed in the previous section.

4.3.1.6 Financial incentives

Financial incentives and assistance

This represents a ‘snapshot’ of the direct and indirect subsidies that could potentially be gained by owners of each electricity technology at the time of writing. The indicator includes the revenues that are available from the Renewables Obligation (using the 2011/2012 price set by Ofgem [12]) and the FiT (using 2011 bandings and assuming a 50:50 split between new and retrofitted domestic installations [14]). None is applicable to nuclear power; however, also included is the carbon tax avoided by ‘zero-carbon’ (at the point of generation) technologies such as nuclear. This assumes that nuclear power replaces the equivalent capacity of combined cycle gas turbines (CCGTs) emitting 400 g CO_2/kWh. The resulting saving is calculated based on the average carbon price in 2010/2011 of £12.69/t CO_2 [203]. No attempt is made to account for future changes in incentives. Additionally, as discussed in Section 3.2.1.6, hidden subsidies are not included. The derivation and breakdown of the results for nuclear power are shown in Table 7.

Table 7: Financial incentives for nuclear power

Number of ROCs received per MWh	0
Value per ROC 2011/12 (£)	n/a[a]
Total ROC incentive (£/MWh)	*n/a*
Value of FiT for <4 kWp in 2011/12	
new build £/MWh)	n/a
retrofit (£/MWh)	n/a
Total average FiT incentive (£/MWh)	*n/a*
Avoided emissions relative to CCGT (t CO_2/MWh)	0.4
Total avoided carbon price[b] (£/MWh)	*5.08*
TOTAL (£/MWh)	**5.08**

[a]n/a: not applicable

[b]Average carbon price from April 2010 to March 2011: £12.69/t CO2 [203]

4.3.2 Environmental data and assumptions

The indicators used for the environmental assessment are shown in Table 2. The key assumptions and data sources are summarised below.

4.3.2.1 Material recyclability

<u>Recyclability of input materials</u>

Material recyclability is the percentage of materials used for construction of a power plant that can potentially be recycled. For most construction materials, the potential recyclability is 100%. The main exception to this is concrete, which is calculated to be 79.4% recyclable [based on 204][19]. Recyclability is calculated using the amounts of construction materials given in Ecoinvent [204], as illustrated in Table 8. The overall recyclability of nuclear plants is modified to reflect the fact that a percentage of materials will have been too highly irradiated to be recycled. This percentage is thought to be as low as 1.44% based on a Swiss study from 1985 [205], reflecting the fact that only a very small volume of the total plant (which includes the entire 'nuclear island') becomes contaminated, assuming normal operation. Corroborating data are lacking in this area; however, a recent study of the AREVA EPR broadly agrees, showing that around 14,000 t of intermediate- (ILW), low- (LLW) and very low-level waste (VLLW) will arise from decommissioning, while the plant has a total mass approximating 400,000 t [206]. This would suggest that an estimate of <5% contamination is reasonable.

The value in Table 8 (81.2%) has therefore been selected as the central estimate for the recyclability of nuclear power. The lower bound (73.3%) corresponds to the amount of material that would be recycled at current UK demolition rates (see Table 9 below).

[19] Concrete is typically crushed into aggregate, which may then be used to manufacture new concrete by adding new cement. In the Ecoinvent v2.2 database [204] concrete contains 1890 kg of aggregate per 2380 kg concrete (= 79.4%).

Table 8: Major materials used for plant construction and their end-of-life recyclability for a 1000 MW nuclear plant (PWR) [204]

Material	Amount (t)	Recyclability (%)
Reinforcing steel	33,700	100
Chromium steel 18/8	21,900	100
Low-alloyed steel	5,570	100
Fibre cement facing tile	5,300	100
Copper	1,470	100
Paper	850	100
Aluminium	200	100
Concrete	402,220	79.4
Total materials	*471,210*	
Gross recyclability of the plant		**82.4% (388,400 t)**
Adjustment for radioactive material		*-1.44%*
Total recyclability of the plant		**81.2% (382,826 t)**

4.3.2.2 Other environmental issues

<u>Environmental (LCA) impacts</u>

The data for nuclear power have been adapted from the PWR in the Ecoinvent 2.2 database [204], which in turn is based on Gosgen PWR in Switzerland. The model was adapted to match UK conditions as follows:

- the current UK electricity mix is used for all relevant life cycle stages of nuclear power occurring in the UK;
- the nuclear fuel cycle assumes burn-up of 53 GWd/tU to approximate likely new-build burn-up rates [195]; and
- it is assumed that no MOX is used and that all spent fuel is sent to conditioning for disposal rather than reprocessing, in line with current UK policy [111].

It should be noted that there is currently a lack of life cycle inventory data on mining of uranium by in-situ leaching (ISL). The Ecoinvent database currently provides data on open-cast and underground mining, but not ISL. ISL currently provides around 36% of global mined uranium, rising from 16% in 2000 [207], and its impacts are likely to be significantly different to those of conventional mining (ISL should have lower energy use and therefore lower associated emissions, but potential acidification of groundwater). Therefore, providing life cycle inventory data on ISL should be a priority of future work in this field.

Following modelling of nuclear power as described above, sensitivity analyses were carried out to estimate the lower and upper bounds for the environmental impacts. As part of these analyses, the effect of end-of-life recycling of all major components was explored using current UK demolition recycling rates, as shown in Table 9. This contrasts with the assumption used in the central estimate in which end-of-life recycling is not considered. No attempt has been made to forecast future recycling rates in the UK due to lack of data.

Additional sensitivity analysis included variations in influential factors, as follows:

- The proportion of MOX fuel used has been varied from 0-8% in line with Ecoinvent assumptions. Given the lack of proposals for MOX use in UK reactors, this 8% figure has been retained as an illustrative example of potential low adoption of MOX.
- The differences between enriching uranium via centrifuge and diffusion have been assessed by varying the proportion using centrifuge from 70-100%. These figures correspond, respectively, to the approximate European market mix in the 2000s [204] and the likely future state as diffusion enrichment continues to be phased out.

Table 9: Current UK end-of-life recycling rates for construction materials

Material	Current UK recycling rate (%)	Source(s)
All metals, exc. aluminium[a]	99	Construction Resources and Waste Platform [208]
Aluminium	95	European Aluminium Association [209]
All plastics[b]	26	Construction Resources and Waste Platform [208]
Concrete	71.5	79.4% maximum potential as discussed in Section 4.3.2.1, modified with 90% current rate as indicated by the Office of the Deputy Prime Minister [210]
Fibre cement facing tile[c]	0	Asbestos Information Centre [211]
Paper	69	Confederation of Paper Industries[212]
Gravel[d]	30	Construction Resources and Waste Platform [208]
Glass fibre reinforced plastic	10	Asokan et al. [213]
Ceramic tiles	64	Construction Resources and Waste Platform [208]
Insulation	18	Construction Resources and Waste Platform [208]
Glass	0	The Waste and Resources Action Programme [214]

[a]Due to lack of material-specific data, assumed rate for generic metals.
[b]Due to lack of material-specific data, assumed rate for generic plastics.
[c]Fibre cement tiles on current buildings often contain asbestos and are therefore routinely disposed of as hazardous waste [211].
[d]Due to lack of material-specific data, assumed rate for generic inert material

Greenfield land use

This indicator is based on visual inspection of the land plots, via Google Maps [215], of all the sites approved by the Government for new nuclear build [17]. These are shown in Table 10.

Table 10: Sites approved for new nuclear build [17]

Site	Proposed capacity (MW)	Land status
Bradwell	1,650	Greenfield
Hartlepool	Grid connection not yet agreed	Brownfield
Heysham	1,650	Greenfield
Hinkley Point	3,340	Greenfield
Oldbury	Connection agreed, capacity t.b.a.	Greenfield
Sellafield	3,200	Greenfield
Sizewell	3,300	Greenfield
Wylfa	3,600	Greenfield

4.3.3 Social data and assumptions

The indicators used for the social assessment are shown in Table 2. The data sources used are discussed below.

4.3.3.1 Provision of employment

Direct and total (including indirect) employment

Employment data have been sourced from the related sectors involved in the life cycle of nuclear power generation. For example, employment related to the extraction of ores and aggregates (for manufacture of concrete, steel and other metals) has been calculated based on material requirements specified in Ecoinvent [204] and employment data from BHP Billiton [216] and the Mineral Products Association [217]. The processing of raw materials into metals is based on labour data from Corus [218]. These sources have been chosen as they provide the most complete dataset. Construction and operational stage figures have been derived from a study by Cogent SSC which specifically addresses nuclear new build in the UK [147]. During the operational stage, maintenance employment is included but only for inspection and installation of replacement parts; employment owing to the manufacture of parts is excluded. Due to a lack of available estimates in the literature, employment during decommissioning is assumed to be 20% of construction employment. This is based on the approximate ratio of decommissioning cost to construction cost, and is in good agreement with the IEA [99], but with a slight upscaling (from 15 to 20%) on the expectation that construction costs are more heavily influenced by the cost of components whereas decommissioning costs are more heavily influenced by employment requirements and will therefore employ more people per unit cost.

Regarding employment related to the fuel cycle (uranium mining, conversion, enrichment and fuel fabrication), data were derived from Areva annual reports [219] as these provide the most complete and appropriate dataset for European plants.

Note that the aforementioned stages together form the total employment estimate. Direct employment is regarded as that resulting only from the construction, operation and decommissioning stages.

4.3.3.2 Human health impacts

<u>Worker injuries</u>

The worker injury results are directly linked to the employment results in that the number of person-years of employment for each life cycle stage is used to calculate the number of expected injuries using Health and Safety Executive data [151] appropriate for the respective type of labour, as shown in Table 11. The exception to this is the uranium mining stage, for which Australian data are used [220] due to the availability of metal ore-specific figures that are not available for the UK or any other uranium-producing countries.

Table 11: Injury rates used to calculate worker injuries in the nuclear life cycle [151, 220]

Life cycle stage	HSE sector-specific injury rate used	Number of injuries per 100,000 workers
Mining of uranium	Metal ore mining	1,485
Conversion	Manufacturing – chemical and chemical products	675.3
Enrichment	Manufacturing – chemical and chemical products	675.3
Fuel fabrication	Manufacturing: Coke, Refined Petroleum Products & Nuclear Fuel	356.8
Manufacture of plant components		
Extraction of ores/aggregates	Other mining	859.6
Processing	Manufacturing (total)	811.8
Manufacture of components	Manufacturing (total)	811.8
Construction	Construction (total)	777.2
Operation	Electricity, gas, steam and hot water supply (total)	553.8
Decommissioning	Construction (total)	777.2

Human toxicity potential & Human health impacts from radiation

These two impacts are estimated as part of LCA (see Section 4.3.2.2).

4.3.3.3 Large accident risk

Fatalities due to large accidents

Large accident fatalities are based on data from the Paul Scherrer Institut [221] drawing on previous work using their historical Energy-Related Severe Accident Database (ENSAD) and, in the case of nuclear power, probabilistic safety assessment [222, 223]. As in the ENSAD, large accidents are defined as those causing at least five fatalities. These results represent Swiss conditions, but have been assumed here to be suitable as an approximation of UK conditions due to the broadly similar population densities of the two countries (Switzerland, 183 people/km^2; UK, 254 people/km^2 [224]) and a lack of UK-specific estimates. Specifically, the nuclear estimate is for an Areva EPR operating in Switzerland in the year 2030. It should be noted that probabilistic safety assessment may be of limited accuracy when used in generic assessments: site-specific factors such as the geography and population of the area surrounding the power plant are important. Nevertheless, in the absence of more reliable data, these results can be used as an indication of the likely range of possible fatalities from a large accident at a nuclear power plant in Europe.

4.3.3.4 Local community impacts & Human rights and corruption

These impacts have not been considered, as they are company-specific and therefore cannot be assessed at the generic technology level.

4.3.3.5 Energy security

Avoidance of fossil fuel imports & Fuel supply diversity

The amount of imported fossil fuel potentially avoided is calculated from the average efficiency of the current UK fossil fuel fleet [calculated from 16] on the basis that a unit of electricity generated by non-fossil capacity displaces a unit generated by fossil capacity. This is described further in Section 3.2.3.6 as is the methodology of the diversity of fuel supply indicator, which has been calculated using 2009 UK data [16]. For uranium supply, UK import data were not available, so EU data from Euratom have been used instead [225], as shown in Table 12. However, since uranium fuel is generally imported to the UK as fuel assemblies manufactured elsewhere, this is arguably equivalent. Results for earlier years have also been calculated using historical reports from Euratom [226-236]. These are discussed in the relevant results section (4.4.3.5).

Table 12: EU uranium supply in 2009 [225] and the resulting fuel supply diversity index

	Percentage of supply (%)
Supply mix to EU	100 (a)
Australia	*21.6*
Canada	*18.68*
Czech Republic(1)	*1.365*
Kazakhstan	*9.07*
Namibia(2)	*2.445*
Niger	*10.54*
Romania(1)	*1.365*
Russia (inc. downblended HEU and re-enriched tails)	*25.4*
South Africa(2)	*2.445*
USA	*1.81*
Uzbekistan	*3.35*
Other	*1.93*
Simpson Diversity Index of net import mix	**0.8396** (b)
UK uranium production	0 (c)
Total fuel supply diversity index (= $c + ab$)	**83.96**

(1)Only combined figures are available for Czech Republic and Romania. A 50:50 split is assumed.
(2)Only combined figures are available for Namibia and South Africa. A 50:50 split is assumed.

Fuel storage capabilities

When quantifying fuel storage for nuclear power, it is more relevant to consider fuel assemblies than uranium itself; therefore this indicator has been quantified using fuel assembly data from Areva [195] on the basis of 50 GWd/tU burn-up.

4.3.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

Neither the AREVA EPR nor the Westinghouse AP1000 are capable of refuelling whilst online, although they do both require enriched fuel. Regarding reprocessing, it is assumed that any new nuclear plants built in the UK will operate on a once-through cycle (i.e. reprocessing will not occur), as this is current policy [111]. Thus, nuclear power deployable in the near future scores one out of three on the nuclear proliferation scale (for further description see Section 3.2.3.7).

4.3.3.7 Intergenerational equity

Abiotic resources (elements and fossil fuels)

These indicators have been estimated as part of LCA (see Section 4.3.2.2).

Volume of radioactive waste and liquid CO_2 for storage

The volume of radioactive waste to be stored is calculated on the basis of lifetime waste production data estimated by the Nuclear Decommissioning Authority [170, 237] for the Areva EPR and Westinghouse AP1000. In calculating the waste produced per unit of electricity produced, the standard capacity factor of 85% is assumed as discussed in Section 4.3.1.1. The results refer to the packaged volume of ILW and spent fuel (i.e. the result includes casks and packing materials in which the waste would be encased). It should be noted that the use of MOX might result in spent fuel with higher heat output as a result of U-236 evolving into Pu-238; the consequences of this on packaging volume are not clear and would require further study [170, 237]. However, the result of this indicator is nevertheless in line with current policy of a 'once-through' fuel cycle.

4.4 Results and discussion

This section presents the assessment results for the nuclear (PWR) option. The summary results are shown in Figure 5, Figure 6 and Figure 7; full results can be found in Appendix 3.

4.4.1 Techno-economic sustainability

This sub-section addresses the techno-economic part of the sustainability assessment of nuclear power. The results are presented in Figure 5 and discussed below.

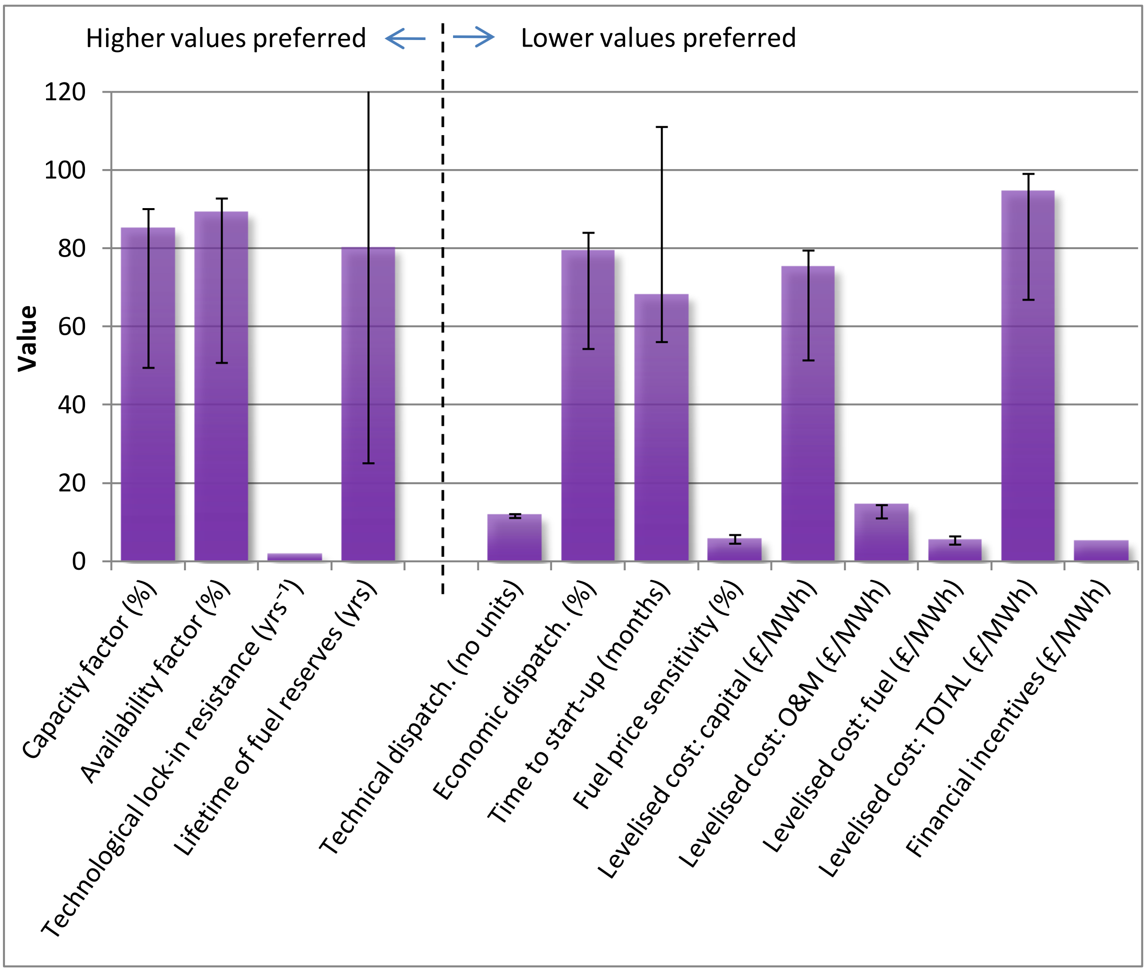


Figure 5: Techno-economic sustainability of nuclear power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases. The value for the upper estimate of *lifetime of fuel reserves* is 675 years. For full results, see Appendix 3.

4.4.1.1 Operability

Capacity and availability factors

Higher availability potentially allows higher capacity factors, effectively reducing the cost (as well as social and environmental impacts) by producing more energy from the same fixed resources. As shown in Figure 5, nuclear power has an availability factor of around 89% and a capacity factor of roughly 85%. These figures are quite similar, reflecting the fact that nuclear plants run continuously due to the low marginal cost of operation. As a result, improving reliability (and thus availability) is likely to have more influence on the capacity factors of nuclear plants than fossil plants: if it was possible to produce electricity all the time, it would be profitable for the operator to do so; in contrast this is not necessarily the case for fossil plants, as profitability depends much more on the cost of fuel and the price of electricity sold to the grid.

Opportunities to improve nuclear availability factors (and therefore capacity factors) are limited given the need to shut down PWRs during refuelling: a period of several days or weeks is required to refuel and carry out planned maintenance, typically every 18 months, meaning availability is unlikely to rise much beyond 90%.

Technical and economic dispatchability

The dispatchability of generators has been the subject of increased scrutiny in recent years as the prospect of wider adoption of intermittent renewables has raised grid management concerns. Nuclear power's technical dispatchability is valued at 11.7 (in a range of 11-12), while its economic dispatchability is rated at 79 (in a range of 54-84). Thus, as lower values are preferable, nuclear power is not as dispatchable as some other options such as gas or coal (see Figure 11 and Figure 17 in Sections 5.4.1.1 and 6.4.1.1, respectively). However, this is mainly an economic issue rather than a technical one, resulting from high capital costs and very low marginal cost. In the future, if the grid changes in such a way that nuclear generators are able to attain greater revenue from electricity sold at times of high demand, it is conceivable that partial load-following would become economically viable. The technical ability to achieve this has been demonstrated elsewhere in Europe, particularly France, and is certainly within the capabilities of new reactors (see Section 3.2.1.1).

Lifetime of global fuel reserves

The lifetime of global nuclear fuel reserves is an important strategic indicator of energy security, as short lifetimes suggest that supply may fail to match demand in the near to medium term, causing price and/or political volatility and potentially disrupting service provision. However, estimating a uranium reserve lifetime meaningfully is difficult due to uncertainties over future discoveries and demand trends. The central estimate of 80 years (Figure 5) is the current ratio of economically recoverable reserves to annual production. However, the incentive to increase exploration comes from increased fuel demand and the resulting increase in prices, therefore it is likely that new reserves or sources will be discovered, or that uneconomic reserves will become economic. Arguably, uranium has a far greater likelihood of extending its reserve lifetime than either coal or gas due to the relatively low level of exploration in recent decades and the increasing possibility of extraction from alternative sources such as phosphates and, at higher prices, sea water. If uranium from phosphates is included in the fuel reserve lifetime, the value increases to 675 years [45]. Additionally, fast breeder reactors provide the possibility of effectively increasing reserve lifetimes to around 34,000 years [45].

4.4.1.2 Technological lock-in resistance

<u>Ratio of plant flexibility and operational lifetime</u>

This indicator gives an estimate of how well nuclear power caters for potential changes in the way that energy is used nationally, accounting for whether it could be modified to tri-generate electricity, heating and cooling, to have negative global warming potential (e.g. integrated biomass and CCS) or to produce hydrogen at high temperatures. As discussed in Section 3.2.1.2, at 1.67 yrs^{-1}, nuclear power is not very resistant to technological lock-in due to its long lifetime and relatively low temperature of around 325°C [110]. Note that this applies only to PWRs and that several other designs (such as molten salt reactors and gas-cooled fast reactors) provide far higher temperatures, but these are beyond the scope of this study.

4.4.1.3 Immediacy

<u>Time to start up</u>

A shorter construction period is preferable because it minimises uncertainty and pay-back period. In this respect, nuclear power performs badly, with plants typically requiring at least five years to build, with a central estimate of 68 months based on the average of the plants sampled in an IEA study [113]. A lower estimate of 56 months is based on AP1000 reactors in China [199]. However, the upper estimate of 111 months illustrates the fact that first-of-a-kind nuclear plants in Europe will take longer than this: the figure is based on the world's first EPR, Olkiluoto 3 in Finland [200]. The last nuclear plant to be built in the UK, Sizewell B, took approximately 86 months [197].

4.4.1.4 Levelised cost of generation

Capital, operational, fuel and total costs

The costs shown in Figure 5 represent the market cost of electricity generation excluding incentives provided by market mechanisms, which are discussed in Section 4.4.1.6. They are not, therefore, the net costs paid by owners. At 10% discount rate, the nuclear option costs 6.7-9.9 pence/kWh, which is broadly comparable to that of coal or gas. However, the cost distribution is arguably just as important as the total: around 80% of the total levelised cost is due to the capital cost while fuel contributes less than 10%. As shown in the next chapter, this contrasts strongly with gas, where 75% of the cost is due to the fuel and less than 20% due to the cost of the power plant [99] (see Figure 11). Nuclear power's high capital component poses a problem in an uncertain market, as it exposes owners to greater losses if plant lifetime is cut short for any reason. This is the case, for example, with German nuclear power plants which will be decommissioned earlier due to a legislative u-turn following the Fukushima incident. Another example of the importance of the capital cost is the 1.6 GW nuclear reactor under construction by EDF at Flamanville, France, which is expected to cost €5 billion (£4.4 billion) [238]. In contrast, the larger 2 GW gas CCGT currently under construction by RWE npower at Willington, UK, has an estimated capital investment of £1 billion [239]. To account for this differing level of risk, it is likely that a potential investor in nuclear (as well as wind or PV) technologies would assess these options at higher discount rates than, for example, gas power, increasing their apparent cost. This would be an attempt to illustrate the higher risk premium and, correspondingly, higher return on investment required to make nuclear, wind or PV profitable.

The levelised costs are estimated using a set discount rate, the level of which may affect the ranking of the options according to differences in the relative magnitude of cost components. As mentioned in Section 3.2.1.4, there is much argument over discounting and its role in sustainability [see, for example, 240], the main premise of which is that high discount rates grossly diminish liabilities that occur far into the future (like nuclear plant decommissioning) and that this is effectively a theft from future generations. However, contrary to popular assertion, nuclear power is in fact penalised by high discount rates as a result of its large initial capital component: while discounting disguises costs in the future, it effectively magnifies costs in the present, meaning all technologies with a large capital component (nuclear, wind and PV) appear more expensive at higher discount rates. As an illustration, raising the discount rate from 5% to 10% increases the cost of nuclear power by more than 60%, while the corresponding increase for gas power is less than 10% [calculated from 99].

4.4.1.5 Cost variability

Fuel price sensitivity

Fuel prices are generally volatile, particularly over periods as long as the lifetime of a nuclear power plant. For nuclear power (see Figure 5), fuel constitutes 4.4-6.7% of the total cost with a central estimate of 5.6% [99]. Additionally, less than half of this is the price of the uranium itself, the remainder being processing costs (conversion, enrichment and fuel fabrication) [120]. This provides a buffer to increases in either extraction costs or processing costs, enabling power plant owners to tolerate a very large increase in the price of either.

4.4.1.6 Financial incentives

Financial incentives and assistance

The quantification and results of this indicator are discussed in Section 4.3.1.6 (see Table 7). From this, it is clear that the EU Emissions Trading Scheme carbon price currently has a very limited effect on the financial viability of low carbon technologies such as nuclear power. The Government has proposed to introduce a carbon price floor from 2013, starting at £16/tCO_2 and rising to £30/tCO_2 by 2020 [28] to strengthen the scheme, which compares to the 2010/2011 average of £12.69/tCO_2 [203]. As shown in Table 7, present day nuclear power effectively avoids a carbon tax of 0.51 p/kWh compared to its total levelised cost of 6.7-9.9 p/kWh (see Section 4.4.1.4). At a carbon tax of £30/tCO_2, the avoided cost would become 1.2 p/kWh, which is clearly a more significant incentive.

The recently announced 'contract-for-difference'[20] will directly subsidise producers of low-carbon electricity by guaranteeing them a set sale price [28]. However, this is not included here as its potential cost is currently unclear.

It should be noted that nuclear power currently receives what could be regarded as a significant indirect subsidy that is not included here. Nuclear installations in the UK are currently only required to insure for a maximum liability in case of an accident of £140 million [241] (although this is currently being amended to the equivalent of €1.2 billion or ~£1.05 billion [242]). This compares to estimated losses to Belarus of $235 billion (~£145 billion) over 30 years as a result of

[20] The 'contract-for-difference' mechanism is essentially a long-term sale price guarantee, with the caveat that any revenue exceeding the set price (or 'strike price') is paid back to the government. For instance, a generator with an agreed strike price of 7 p/kWh is guaranteed that income – if the electricity is sold for 4 p/kWh, the government pays the generator the remaining 3 p/kWh – but if the generator sells for 8 p/kWh, the extra 1 p/kWh is paid back to the government [28].

the Chernobyl accident [243]. The difference arguably represents a subsidy that plant owners receive by not being required to insure their true liability (although it is also true that such large sums cannot be insured by the market). Ultimately, the amount paid by the owner in the event of a large accident would depend on many immeasurable variables, such as the size of the company and the policies of the national government.

4.4.2 Environmental sustainability

This sub-section addresses the environmental part of the sustainability assessment of nuclear power. All environmental indicators, except for material recyclability and greenfield land use, have been estimated using life cycle assessment (LCA) and the CML 2001 impact assessment methodology (the November 2009 update) [59, 139]. GaBi v4.4 LCA software [244] and the Ecoinvent v2.2 database [204] have been used for these purposes. The central estimates are based on modelling undertaken in this study, but included in the possible range of values are the following models from other sources:

- a PWR in the USA taken from Ecoinvent [204], assuming a once-through cycle and a 30:70 split between diffusion and centrifuge enrichment, respectively;
- a PWR in Switzerland, also taken from Ecoinvent [204], assuming 8% MOX use and 100% centrifuge enrichment; and
- an AREVA EPR in the UCTE region of Europe in 2025, taken from the NEEDS LCI database [245] under the pessimistic scenario (“pessimistic/BAU”).

The results are presented in Figure 6 and discussed below.

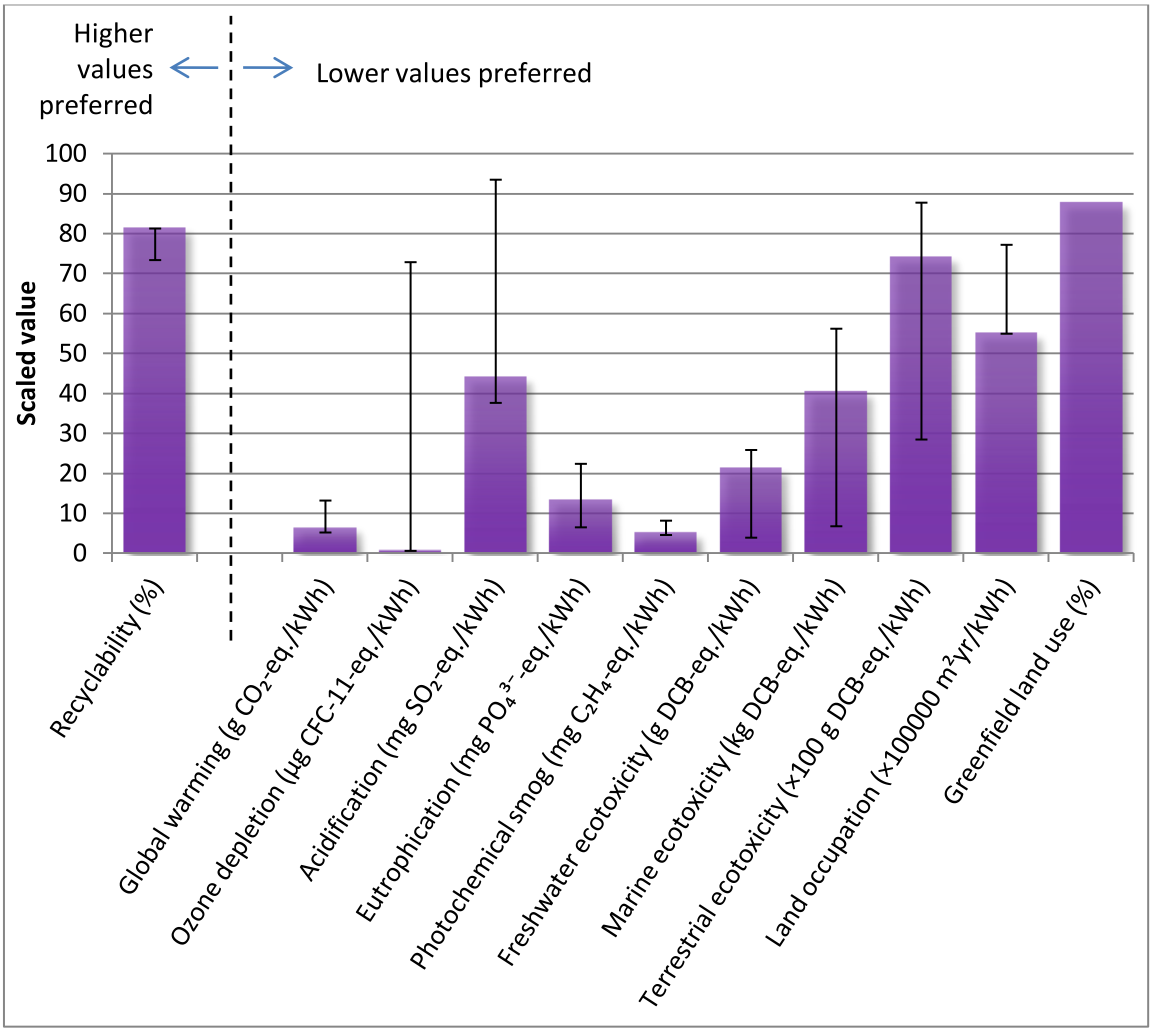


Figure 6: Environmental sustainability of nuclear power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled by multiplying or dividing their original values by the factors shown in brackets. Bar height represents the central estimate in all cases. Some indicators have been scaled up to be viewed more easily by multiplying their original values by the factor shown in brackets. For full results, see Appendix 3.

4.4.2.1 Material recyclability

Recyclability of input materials

Figure 6 (and Table 8 in Section 4.3.2.1) shows that the potential recyclability of a nuclear power plant is around 81%, being limited mainly by extensive use of concrete[21]. The lower estimate illustrates the fact that, under current recycling rates for major materials (see Table 9 in Section 4.3.2.2), the result is reduced to 73%. Long term neutron irradiation precludes the recycling of

[21] Concrete cannot be recycled in the traditional sense: it is typically crushed into aggregate, some of which is used to manufacture new concrete, but this requires the addition of new cement. A large proportion of crushed concrete is also 'downcycled' for various applications such as the back-filling of quarries and the engineering of landfill sites. Some used concrete is landfilled.

some materials, but as discussed in Section 4.3.2.1, for a large plant the mass of contaminated material is estimated to range between 5000 and 14,000 tonnes [205, 206], which constitutes less than 5% of the total plant mass. As a result, the recyclability of nuclear power plants is not as limited as might be expected.

To illustrate the potential implications of recycling on environmental impacts, a sensitivity analysis has been carried out comparing assumptions of no recycling with recycling components at current UK rates (see Table 9 in Section 4.3.2.2). The results show that end-of-life recycling has a small, positive impact, as shown in Table 13. The most significant improvement, 9.83%, is seen for eutrophication potential because 26% of this impact in the no-recycling case is due to construction and component manufacture (see Appendix section 14.1.2), meaning recycling components negates some of the impact. The effect on global warming potential is small (2.14%) because, despite construction causing 30% of the impact in the no-recycling case (see Appendix section 14.1.2), more than half of this is due to electricity use during construction which cannot be negated by recycling components.

Table 13: Percentage reduction in impacts due to recycling of nuclear plant components at end-of-life, using current UK recycling rates

Impact	Reduction of impact at current UK recycling rates[a] relative to no recycling (%)
Global warming potential	2.14
Ozone depletion potential	0.61
Acidification potential	1.84
Eutrophication potential	9.83
Photochemical smog potential	3.21
Freshwater eco-toxicity potential	1.2
Marine eco-toxicity potential	1.66
Terrestrial eco-toxicity potential	0.77

[a] Aluminium 95%, other metals 99%, plastics 26%, concrete 71.5%, fibre cement facing tile 0%, paper 69%, gravel 30%, glass fibre reinforced plastic 10%, ceramic tiles 64%, insulation 18%, glass 0% (see Section 4.3.2.2).

4.4.2.2 Global warming potential (GWP)

As shown in Figure 6, the central estimate for the GWP of nuclear power is 6.2 g CO_2 eq./kWh in a range of 5.1-13.1 g CO_2 eq./kWh. This is similar to other present-day estimates for PWRs in literature: for example, 8 g CO_2 eq./kWh (PSI [246]); 5.5 g CO_2 eq./kWh (AEA Energy and

Environment [137]). In comparison, the current average GWP from the UK electricity mix is 584 g CO_2 eq./kWh [204]. The impact is accrued mainly during mining and milling (31%), construction (30%) and conversion (19%).

4.4.2.3 Ozone layer depletion potential (ODP)

The estimated central value for ODP is 0.54 μg CFC-11 eq./kWh while the maximum value is two orders of magnitude higher at 73 μg CFC-11 eq./kWh. This is due to the sensitivity analysis exploring different enrichment technologies (see Section 4.3.2.2): the United States Enrichment Corporation (USEC) diffusion enrichment plant in Paducah, Kentucky, is unusual in its use of Freon (CFC-114)[22] as coolant, meaning any uranium enriched at this facility has a large associated ODP. Indeed in 2002 this single facility emitted more than half of the USA's total industrial airborne Freon emissions [247]. However, this is of little consequence for nuclear power in the UK and is shown here only to illustrate worst-case values for ODP. In the central case, mining and milling contribute 39% of the total ODP impact, while conversion causes 30%.

4.4.2.4 Acidification potential (AP)

The AP of nuclear power is estimated at 0.044 g SO_2 eq./kWh within a range of 0.038-0.093 g SO_2 eq./kWh. By far the biggest contributor to this impact (51.1%) is the emission of sulphur dioxide and nitrogen oxides during uranium milling. The upper estimate of 0.093 relates the Ecoinvent model of a PWR in the USA and is primarily due to the use of coal power during construction and diffusion enrichment at the USEC enrichment plant [204].

4.4.2.5 Eutrophication potential (EP)

The nuclear life cycle has a EP of 0.013 g PO_4^{3-} eq./kWh, primarily due to emission of phosphates and nitrogen oxides throughout the life cycle, with uranium milling being the biggest contributor (42.2%). The central estimate lies within upper and lower bounds of 0.006 and 0.022 g PO_4^{3-} eq./kWh.

[22]Although the manufacture of CFCs in the US ended in 1995 in accordance with the Montreal Protocol, there are still large stockpiles of Freon which can be used until exhausted.

4.4.2.6 Photochemical oxidant creation potential (POCP)

The POCP of the nuclear life cycle is estimated to be 0.005 g C_2H_4 eq./kWh within a range of 0.0045-0.0081 g C_2H_4 eq./kWh. Again, uranium milling is the biggest contributor at 48.9% of the total with mining and construction of the plant additionally causing 15% of the impact each.

4.4.2.7 Water eco-toxicity

Freshwater eco-toxicity potential (FAETP)

Nuclear power has an FAETP of 21 g DCB eq./kWh. The central estimate lies within a range of 4-26 g DCB eq./kWh with the EPR model from the NEEDS database providing the lowest result[23]. In the central case, over 70% of this impact is due to long-term emissions of metals such as vanadium, copper and beryllium from uranium mill tailings. This is a good illustration of the need for further LCA work on mining via in-situ leaching (ISL), as discussed in Section 4.3.2.2, since ISL mines do not leave tailings behind (although the same metals may be distributed in groundwater instead).

Marine eco-toxicity potential (MAETP)

The nuclear life cycle has an MAETP of approximately 40 kg DCB eq./kWh. About 68% of this is due to long term emission of metals such as beryllium, vanadium and selenium from uranium mill tailings to freshwater, which eventually has an impact on marine environments. The range of results spans 7-56 kg DCB eq./kWh, with the EPR from the NEEDS database again providing the lowest figure[23].

4.4.2.8 Land use and quality

Terrestrial eco-toxicity potential (TETP)

The terrestrial eco-toxicity result for the nuclear life cycle is 0.7 g DCB eq./kWh within a range of 0.3-0.9 g DCB eq./kWh. As is the case for freshwater eco-toxicity, more than half of this impact is due to emission of heavy metals to air from uranium mill tailings. The remainder is due to

[23] The large difference between the central estimate and the lower bound is likely due to changes in the life cycle inventory and characterisation factors that were implemented by Ecoinvent and CML after the NEEDS model was compiled [see 248]. This also affects the Swiss PWR taken directly from Ecoinvent (see start of Section 4.4.2). The changes particularly affect the inventory and characterisation of heavy metals emitted from uranium mill tailings, causing later modelling to show higher eco-toxicity impacts due to better accounting of emissions.

emissions of heavy metals such as chromium, mercury and arsenic in the steel and copper production chains.

Land occupation

Over the whole life cycle, nuclear power occupies approximately 0.00055 m^2yr/kWh, around half of which is the plant itself. Most of the assessed models provide very similar results (0.00053-0.00055 m^2yr/kWh) apart from the Ecoinvent model of an American PWR which gives a higher land occupation of 0.00077 m^2yr/kWh. The main reason for this difference is simply that the assumed fuel burn-up is lower in the latter model than in the central case (37.5 c.f. 53 GWd/tU), meaning less electricity is produced from the same plant area.

Greenfield land use

The greenfield land use indicator is intended to describe the percentage of new power plants likely to be built on greenfield land and as such only the operational stage is considered. Of the eight sites currently approved for new nuclear build in the UK, all but one (Hartlepool) is greenfield, despite all of them being adjacent to existing nuclear sites. Therefore 87.5% of new nuclear power plants will be built on greenfield land (see Figure 6 and Table 10).

4.4.3 Social sustainability

This sub-section addresses the social part of the sustainability assessment of nuclear power. The results are presented in Figure 7 and discussed below.

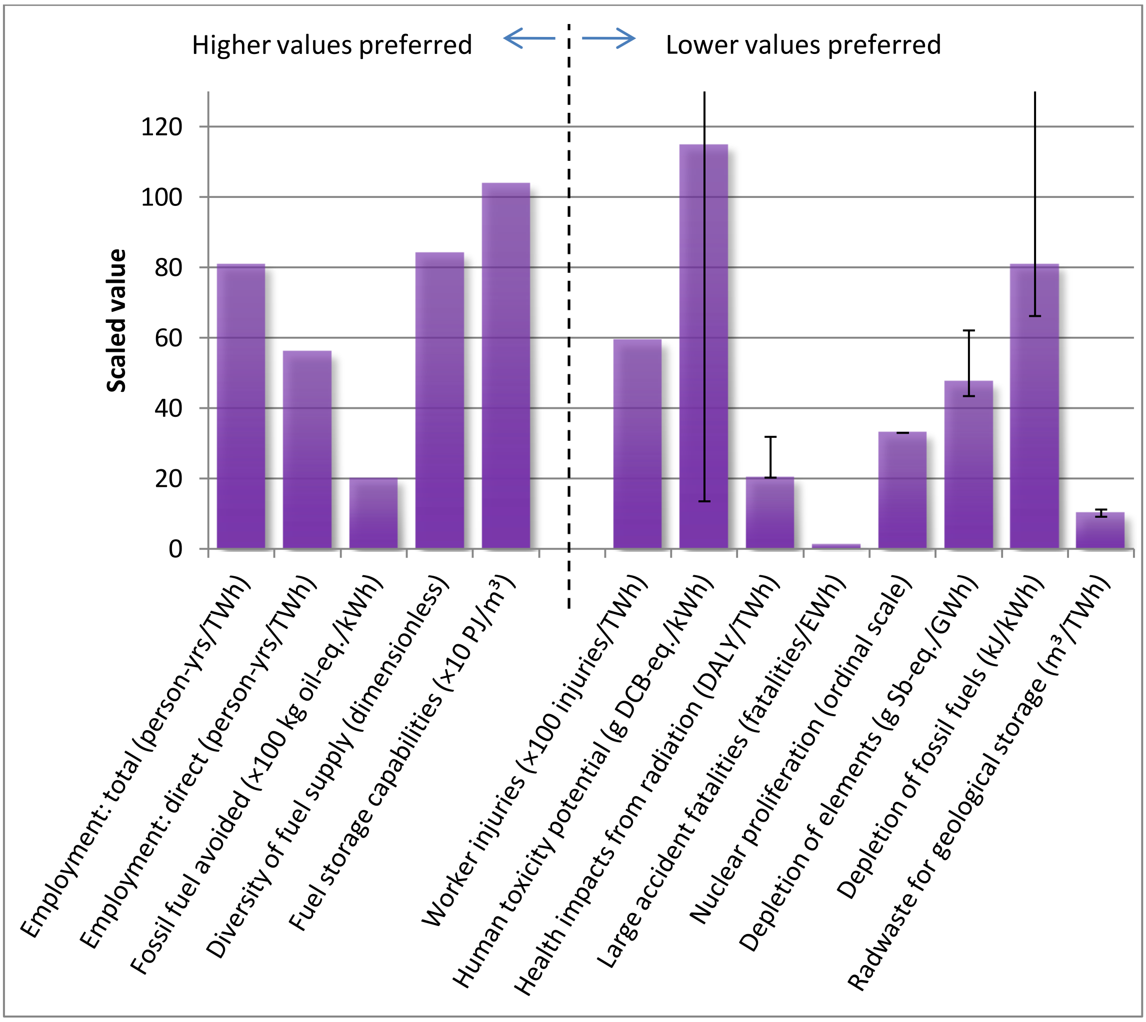


Figure 7: Social sustainability of nuclear power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying their original values by the factor shown in brackets. Bar height represents the central estimate in all cases except *radwaste for geological storage*, for which the bar height represents the average value for the AREVA EPR and Westinghouse AP1000. The value of the upper estimate for *human toxicity potential* is 135 g DCB eq./kWh. The value of the upper estimate for *depletion of fossil fuels* is 151 kJ/kWh. For full results, see Appendix 3.

4.4.3.1 Provision of employment

Total employment

Total employment estimates in Figure 7 comprise direct and indirect employment. The former is related to the power plant erection, operation, maintenance and decommissioning while the latter refers to jobs in fuel mining and production, waste management and other services to the plant over its lifetime. The results show that nuclear power provides 81 person-years/TWh of employment, most of which is direct (i.e. specifically related to the power plant site). Approximately 53% of total employment is due to the operation of the power plant itself, with a twin-reactor site of 2.7 GW capacity expected to need around 800 full-time employees for its lifetime of 60 years [147]. Although the construction of the plant is expected to require over 2000 full-time employees, this only lasts for about six years and thus only contributes approximately 13% of total life cycle employment.

Direct employment

When indirect employment is excluded from the total, nuclear power provides 56 person-years/TWh, mainly due to the operational stage as mentioned above.

4.4.3.2 Human health impacts

Worker injuries

The nuclear life cycle is estimated to cause 0.6 injuries/TWh (Figure 7). As shown in Table 11 (see Section 4.3.3.2) injury rates are particularly high in the mining sector, meaning uranium mining causes 27.4% of nuclear life cycle injuries despite only representing 13.5% of total employment. The most significant stage of the life cycle in terms of worker injuries is the operational stage, causing 40.4% of injuries simply due to its long duration.

Human toxicity potential (HTP), excluding radiation

Emissions of heavy metals including arsenic and chromium are substantial in the nuclear life cycle, the bulk coming from uranium mill tailings, ultimately giving nuclear power a relatively high HTP of 115 g DCB eq./kWh. The range identified spans 14-135 g DCB eq./kWh, with the NEEDS EPR model providing the lowest estimate which may be explained by modelling anomalies (see Note 23 in Section 4.4.2.7).

Total human health impacts from radiation

The health impact of radiation from the nuclear life cycle is 20.3 disability-adjusted life years (DALYs) per TWh within a range of 20.3-31.9 (Figure 7). Approximately 90% of this impact is caused by emissions to air of radon-222 from uranium mine tailings over a period of thousands of years, with the remainder being emissions of isotopes like carbon-14 during power plant operation (although this will vary with reactor type).

To put this figure in context, the annual health impact from global nuclear electricity generation (2600 TWh in 2010 [249]) would be roughly 53,000 DALYs. In comparison, COMEAP [250] estimates that, as a result of anthropogenic air pollution, up to 597,000 life-years were lost in 2008 in the UK alone (approximately 3.5 life-days per person); this refers to premature deaths only and excludes disability induced by the pollution.

4.4.3.3 Large accident risk

<u>Fatalities due to large accidents</u>

The risk of large accidents is a particularly important issue for nuclear power, particularly in terms of public perception. This is, in part, due to the widespread suspicion and fear engendered by the accidents at Three Mile Island and Chernobyl, particularly the large number of deaths ultimately caused by the latter. Estimates including latent deaths range from around 8,250 [251] to over 200,000 [252]: numbers only rivalled in the energy sector by the Banqiao dam failure in China in 1975, which caused at least 25,000 deaths [253] (possibly 230,000 including subsequent disease and famine [254]). However, it is important to recognise the fact that, in terms of large accident fatalities from nuclear plants, Chernobyl is the only data point. Additionally, it represents an entirely different reactor design (RBMK-1000: a graphite moderated, water cooled reactor) to those that could be built in the UK. It should also be noted that large accidents occur at a higher frequency in other energy chains, but with fewer consequences per incident.

Using probabilistic safety assessment, as shown in Figure 7, the Paul Scherrer Institut estimate that a new nuclear power station such as the EPR would cause 1.22×10^{-3} fatalities/PWh [221]. In other words, if global nuclear capacity was replaced with EPRs and electricity production levels remained the same as the present, one fatality would be expected every 315 years as a result of large accidents [calculated from 249]. This is clearly an extremely low fatality rate and is due to a low probability of occurrence. However, a single large accident at an EPR in Europe, if it were to happen, could cause up to 49,000 fatalities [221]. The difference in these two results illustrates the fact that this issue is perhaps as much about risk perception as objective estimates: many people are more willing to accept a situation with a high probability of minor detriment than one with a low probability of great detriment, even if the total detriment caused by the former is higher.

4.4.3.4 Local community impacts and human rights & corruption

As mentioned in Section 4.3.3.4, these impacts have not been considered because they are company-specific and therefore not applicable for technology assessment. For further discussion, see Section 3.2.3.

4.4.3.5 Energy security

<u>Avoidance of fossil fuel imports</u>

The fossil fuel plants that currently provide around 75% of UK electricity are estimated here to use, on average, 200 tonnes of oil-equivalent (toe) per GWh (see Section 3.2.3.6). The avoidance of this by nuclear capacity represents a national increase in resilience to fossil fuel price volatility. However, it should be noted that nuclear power is generally less dispatchable than fossil fuelled plants, therefore an increase in nuclear capacity may force the remaining fossil plants to operate less efficiently as they are increasingly needed to follow load. Therefore, the figure of 200 toe is likely an overestimate.

<u>Diversity of fuel supply mix</u>

This indicator reflects the resilience of national electricity production to fuel supply disruptions, whether they are economic, technical or political. Uranium, being an energy-dense fuel traded on the world market, is not specifically imported to the UK. Rather, large electric utilities normally buy prefabricated fuel assemblies on the European market. For this reason, EU uranium import figures are more appropriate and have been used here. Since no uranium is produced in the UK, the overall UK diversity of fuel supply score is 0.84 (= 0 + (0.84 × 1); see Section 3.2.3.6 for the estimation methodology). This is a relatively high score, reflecting the fact that the EU (and therefore UK) supply mix for uranium is diverse and evenly split, coming from a total of more than 12 countries, with the main suppliers (Russia, Australia and Canada) contributing roughly equal amounts [225]. As shown in Figure 8, the diversity of European uranium supply has been quite constant over the last decade, staying in a range of 0.79-0.84.

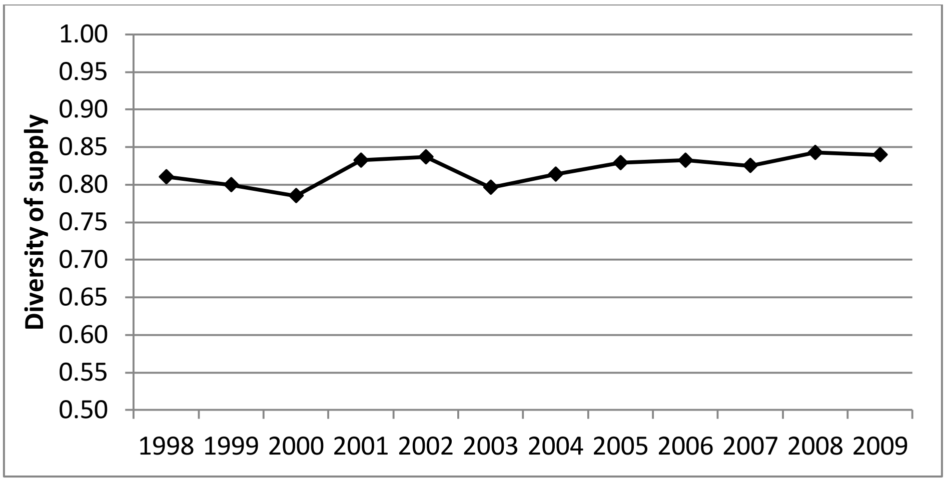


Figure 8: Historical results illustrating the diversity of European uranium supply

Fuel storage capabilities

This indicator shows inherent resilience: energy dense fuels are physically easier to transport and store to be used when supply is problematic. In this respect, nuclear power is by far the best option available. Assuming a burn-up of 50 GWd/tU, conservative for new reactors [see, for example 195], a nuclear fuel assembly has an energy density of 10,367,000 GJ/m^3 (Figure 7). Note that fuel storage should not be confused with electricity storage (which is not considered here).

4.4.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

Nuclear proliferation clearly only applies to the nuclear option and as such is considered in a relatively simple form here. However, different combinations of reactor type and fuel cycle present unique proliferation problems, as discussed in Section 3.2.3.7. New nuclear build in the UK is likely to involve PWRs on a once-through cycle with no reprocessing of spent fuel. The only proliferation problem this presents is its requirement for enriched uranium, which arguably contributes to the spread of enrichment technology worldwide. On the scale used in this assessment, this gives a score of one out of three, or 33% (given the above three components of this indicator). If reprocessing of spent fuel occurs at some point in the future, this increases proliferation risk by separating uranium and/or plutonium, stores of which might then become targets of theft or terrorist attack. This would raise the score to two out of three, or 67%. The worst case would involve the use of reprocessing and enrichment in a fuel cycle involving a Magnox or CANDU reactor, from which high quality plutonium can be extracted relatively easily. Nothing of this sort has been proposed for the UK at the time of writing.

4.4.3.7 Intergenerational equity

Use of abiotic resources (elements)

As indicated in Figure 7, use of abiotic elements in the nuclear life cycle totals 47.4 g Sb eq./GWh (with a range of 43.4-62.1). 90% of this impact is due to the use of chromium, copper, molybdenum and nickel throughout the nuclear life cycle, primarily during fuel fabrication and construction of the power plant itself.

Use of abiotic resources (fossil)

Nuclear power consumes 80.7 kJ/kWh of fossil-derived resources (with a range of 66.2-150.5). Mining, milling and construction of the plant together account for 59% of this impact. The maximum value of 150.5 kJ/kWh is derived from the model of a PWR in the USA, with electricity use during diffusion enrichment accounting for most of the increase (30% of the total value: 44.4 kJ/kWh).

Volume of radioactive waste and liquid CO_2 to be stored

Production of radioactive waste (and CO_2 from CCS) represents a burden of storage and monitoring being passed to future generations. It also represents a burden of risk, but at the present time this cannot be quantified due to the lack of operating experience with geological repositories. Average lifetime waste production by the two nuclear reactors currently proposed for new build in the UK is estimated at 10.16 m^3/TWh. This is the packaged volume and includes spent fuel as well as all intermediate level waste from decommissioning, such as reactor components, filters and resins. The value represents a total lifetime waste volume of 5581 m^3 for a single AP1000 and, due to its greater rated capacity, 6647 m^3 for an EPR. By comparison, the UK's current and future HLW and ILW arising from past and current commitments, but not including new build, is 489,330 m^3 [255]. It should be noted that this does not include LLW, most of which is now recycled or disposed of in near-surface facilities. The nuclear option, therefore, poses complex intergenerational dilemmas: whilst it passes the burden of radioactive waste management onto future generations, it could also play a significant role in preventing climate change for the benefit of future generations as well as our own [256].

4.5 Data quality in the nuclear power assessment

Sustainability assessment of electricity generation options requires the sourcing and calculation of large amounts of data. This is particularly true when the full life cycle is considered, as is the case here. Accordingly, data quality has been assessed for each technology considered in this study using a methodology described in Appendix 4. In brief, the quality of every indicator result was rated as ‘low’, ‘medium’ or ‘high’ against each of the following criteria:

- Time specificity
- Geographical specificity
- Technological specificity
- Completeness of data
- Quality of data source(s)
- Auditability
- Validation

Consideration of these criteria is recommended by, for example, the PAS 2050 standard, and additionally draws on work in the fields of LCA [257] and decision analysis [258] (see Appendix 4 for discussion). The resulting ratings were then aggregated using Tesla v1.11 decision support software [258] with the help of the Advanced Evidence Support Logic v1.8 module.

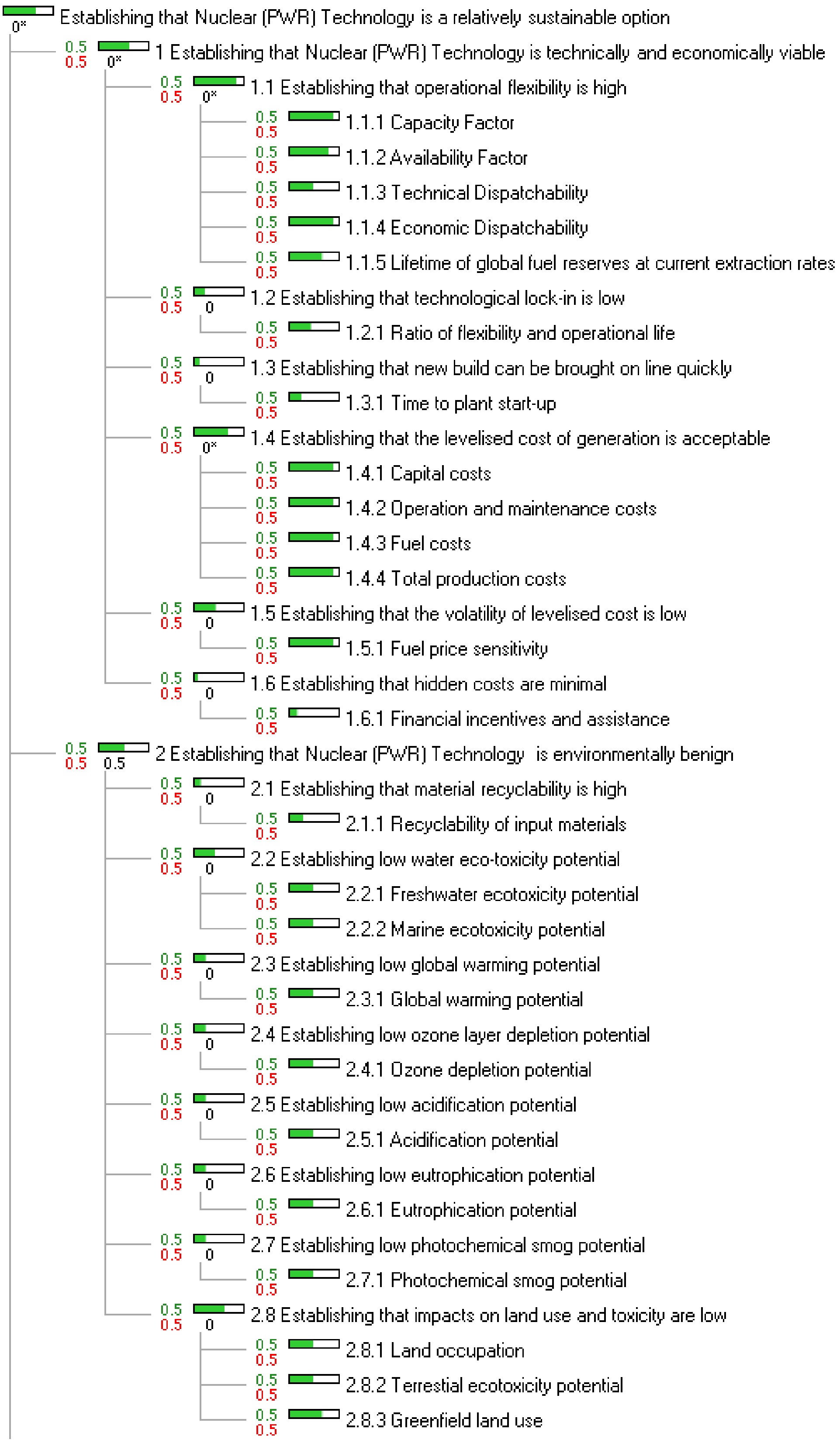
Figure 9 shows a summary of the data quality of the nuclear power assessment. As indicated, the overall data quality is rated at 66% (where a rating of 100% would indicate perfect quality). This result reflects the fact that some underlying data used in the assessment precluded the possibility of some indicators being rated as ‘high’ quality for all of the criteria listed above. For example, results for both *direct* and *total employment* were rated as ‘medium’ against the ‘completeness of data criterion’ because employment during decommissioning was based on an assumption rather than primary or secondary data. Additionally, the results of indicator *diversity of fuel supply mix* cannot be validated because they have been developed in this work for the first time.

As the quality assessment is hierarchical, when an individual indicator result does not perfectly fulfil all seven criteria, this lowers the score of the groups to which it belongs: for instance, if *worker injuries* is rated as low quality, this reduces the score of the sub-group *human health impacts*, which in turn reduces the score of the group *social*, which in turn reduces the overall score of the dataset. In cases where several indicators rely on the same data (i.e. dependency is high), the effect of any uncertainty on a group or sub-group is amplified because a single error in the data would affect several of that group’s constituent indicators rather than just one.

The weakest of the three ‘pillars’ in this sustainability assessment is the environmental group, scoring 52.8%. This is mainly due to the fact that the LCA modelling is based not on a generation III+ PWR in the UK, but on modification of a generation II PWR in Switzerland, meaning that, while data is complete and of good quality, it is not of the highest specificity in terms of time, geography or technology. However, the main reason the environmental group scores lower than the others is simply the fact that most environmental indicators are derived from LCA and share the same data sources. Therefore, dependency between indicators is high, meaning confidence in the results of the group as a whole is reduced slightly as discussed above.

Overall, the data quality of the nuclear power sustainability assessment is thought to be good considering the purposes of this study: that is, an assessment of generic nuclear power as might be built in the UK. Improvements could be made by focusing on lower rated areas shown in Figure 9 as shorter green bars. Thus, the focal points of potential future work should primarily be:

- improving the environmental group by conducting life cycle assessments specifically on generation III+ PWRs under UK conditions;
- improving the assessment of financial incentives and assistance by extending the current data to include hidden subsidies as discussed in Section 3.2.1.6; and
- improving large accident risk estimates by conduction probabilistic safety assessment under UK conditions, as discussed in Section 4.3.3.3.



Establishing that Nuclear (PWR) Technology is a relatively sustainable option
1 Establishing that Nuclear (PWR) Technology is technically and economically viable
1.1 Establishing that operational flexibility is high
1.1.1 Capacity Factor
1.1.2 Availability Factor
1.1.3 Technical Dispatchability
1.1.4 Economic Dispatchability
1.1.5 Lifetime of global fuel reserves at current extraction rates
1.2 Establishing that technological lock-in is low
1.2.1 Ratio of flexibility and operational life
1.3 Establishing that new build can be brought on line quickly
1.3.1 Time to plant start-up
1.4 Establishing that the levelised cost of generation is acceptable
1.4.1 Capital costs
1.4.2 Operation and maintenance costs
1.4.3 Fuel costs
1.4.4 Total production costs
1.5 Establishing that the volatility of levelised cost is low
1.5.1 Fuel price sensitivity
1.6 Establishing that hidden costs are minimal
1.6.1 Financial incentives and assistance
2 Establishing that Nuclear (PWR) Technology is environmentally benign
2.1 Establishing that material recyclability is high
2.1.1 Recyclability of input materials
2.2 Establishing low water eco-toxicity potential
2.2.1 Freshwater ecotoxicity potential
2.2.2 Marine ecotoxicity potential
2.3 Establishing low global warming potential
2.3.1 Global warming potential
2.4 Establishing low ozone layer depletion potential
2.4.1 Ozone depletion potential
2.5 Establishing low acidification potential
2.5.1 Acidification potential
2.6 Establishing low eutrophication potential
2.6.1 Eutrophication potential
2.7 Establishing low photochemical smog potential
2.7.1 Photochemical smog potential
2.8 Establishing that impacts on land use and toxicity are low
2.8.1 Land occupation
2.8.2 Terrestial ecotoxicity potential
2.8.3 Greenfield land use

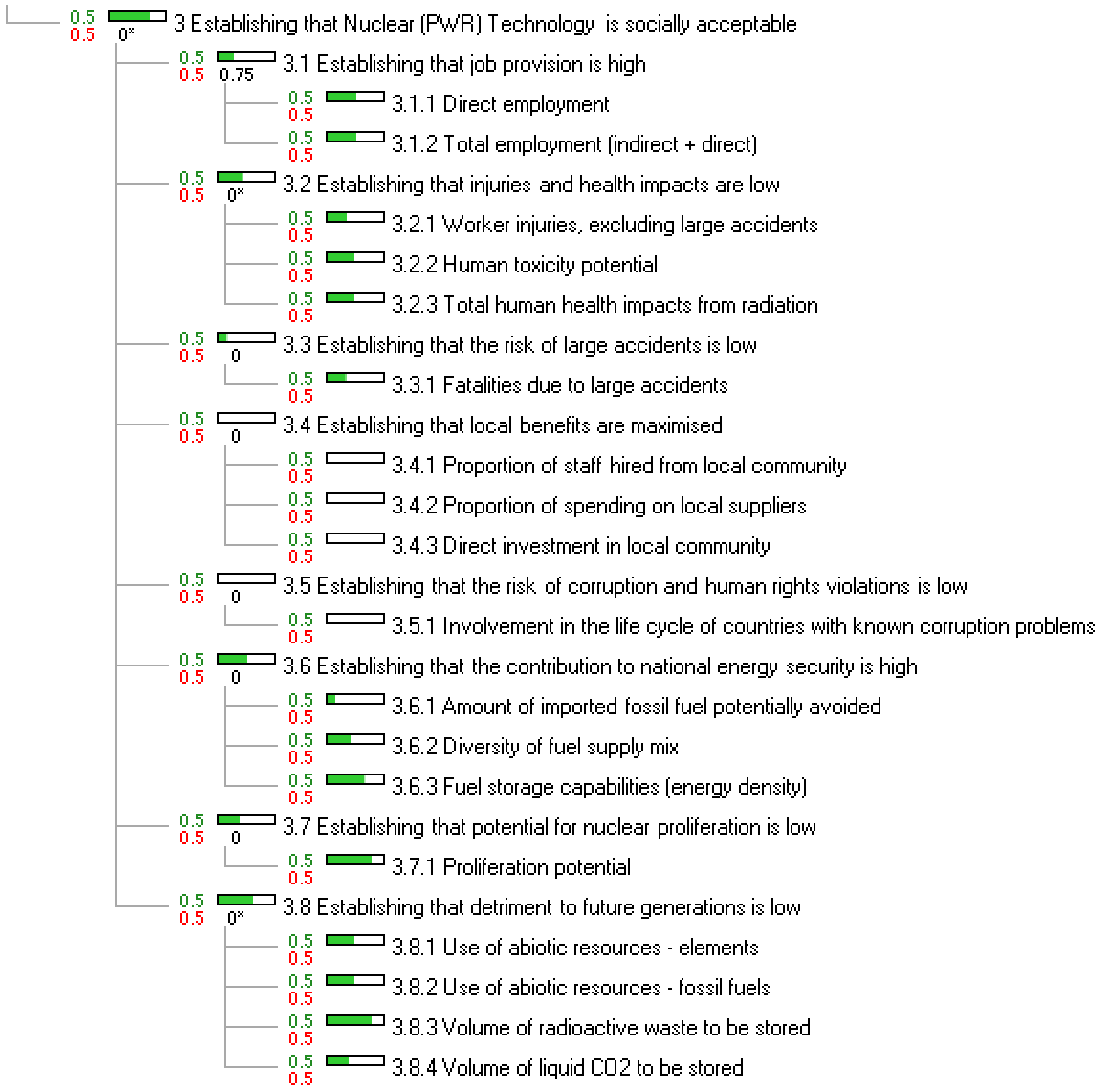


Figure 9: Data quality summary for the sustainability assessment of nuclear power

4.6 Summary

The outcomes of the sustainability assessment of nuclear power may be summarised as follows:

- The cost of nuclear power is £67-99/MWh at 10% discount rate, with a central estimate of £95/MWh. The capital component is large, accounting for around 80% of the total; nuclear power is therefore less attractive at higher discount rates.
- Total cost is virtually insensitive to fuel price changes, and although conventional uranium reserves have a relatively short expected lifetime of around 80 years, this could increase to 675 years with phosphate resources and over 34,000 years if fast reactors become widespread.
- Nuclear power is quite non-dispatchable, but this is mainly an economic issue rather than a technical one, meaning partial load-following is achievable depending on peak electricity prices.
- Environmentally, nuclear power has relatively low impacts in terms of global warming, ozone layer depletion, acidification, eutrophication, photochemical oxidant creation and land occupation. The main exception is freshwater eco-toxicity, however most of this impact is due to uranium mill tailings and it is not currently known how this will be affected by the increasing adoption of in-situ leaching.
- Nuclear power scores high for the energy security indicators.
- It does, however, have a relatively high health impact from radiation (although it is argued that this impact is extremely small when put in an appropriate context).
- The intergenerational impacts of nuclear power are arguably significant, as ~6000 m^3 of waste requires geological storage per reactor lifetime. However this should be weighed against the intergenerational impact of climate change, for which nuclear is a good option.
- Finally, nuclear power has the potential to cause a very high number of fatalities in a single incident, although the rate at which these fatalities are expected to occur is extremely low.

The next chapter focuses on power from natural gas and discusses its life cycle sustainability.

5 Natural gas power

This chapter describes the sustainability assessment of electricity from natural gas from the perspective of potential new build in the UK: it is therefore focused on combined cycle gas turbines (CCGTs). The chapter starts in Section 5.1 with an overview of the current situation with respect to power from natural gas in the UK. This is followed by a summary of the gas power life cycle and its related sustainability issues in Section 5.2, while Section 5.3 describes the data sources and assumptions that were used to assess gas power. Section 5.4 then presents and discusses the results. Finally, Section 5.5 summarises the data quality analysis of this assessment.

5.1 Natural gas power in the UK: the current situation

Historically, the UK has been a major producer of natural gas, exploiting its indigenous reserves in the North Sea. This was particularly true throughout the 1990s, in large part due to the 'dash for gas' that occurred after the electricity industry was privatised in 1990. However, yields from the UK continental shelf have been declining since 2000, leading to a shift in status for the UK to net importer in 2004 [5]. As of 2010, indigenous production and imports are approximately equal [5].

The aforementioned 'dash for gas' involved the widespread adoption of CCGTs in the UK, in part due to their extremely high efficiency relative to traditional fossil fuelled power stations: a typical new station is expected to have an efficiency of 55-60% (net calorific value basis) [259, 260] as a result of the combination of gas and steam turbines (Brayton and Rankine cycles). There are currently around 40 operating CCGTs in the UK, with a combined capacity of 34 GW [130]. These provide 46% of the UK's electricity supply [5]. Therefore, in terms of both installed capacity and generation, CCGTs are therefore the most common type of electricity generating technology in the UK. Open cycle gas turbines (OCGTs) also contribute to the electricity mix, mainly to assist with load-following, but their total capacity is less than 1.6 GW [130].

As of May 2011, National Grid had agreed, or received proposals, to connect 16.2 GW of new CCGT capacity to the grid by 2018 [27]. Therefore, the contribution of CCGTs to the electricity mix will increase in the near future.

5.2 Natural gas power life cycle and sustainability issues: an overview

The life cycle of gas power is shown in Figure 10. Norway is the principle supplier to the UK, accounting for around 58% of imports in 2009 [16]. However, the UK is gradually relying more heavily on internationally traded liquefied natural gas (LNG), which accounted for 25% of imports in 2009 [16]. This situation illustrates the fact that energy security is a major sustainability issue in the gas life cycle (as discussed in Section 3.2.3.6). Additional issues related to gas production include worker safety and accident risk.

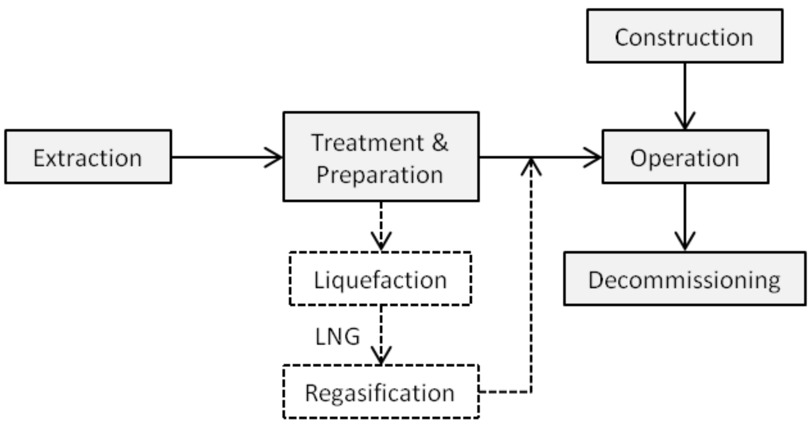


Figure 10: The life cycle of natural gas power (LNG: liquefied natural gas; the broken line indicates optional parts of the life cycle)

After extraction, natural gas is traditionally transported long distances by pipeline with the major issues for consideration being leakage of gas and its potential impact on climate change as well as the use of halogenated gases as fire retardants leading to ozone layer depletion. In the case of LNG, gas is liquefied via cooling prior to being transported in specially designed oceanic carriers. This liquefaction process decreases the volume of the gas by approximately 600 times. Upon arrival to the UK, LNG is regasified via heating before being fed into the national gas grid. The sustainability issues unique to LNG include the extra energy (and associated emissions) required for liquefaction and regasification, as well as the extra fossil fuel burned during transportation.

Construction and operation of a CCGT plant typically last 3-4 years and 20-30 years, respectively [112, 260]. Specific issues of relevance to these stages include the high level of employment generated during the construction period (typically over 1000 people [see, for instance, 260]) and the relative speed with which the plants can be brought online. As discussed above, CCGTs are extremely efficient relative to traditional fossil fuelled power stations, meaning more electricity is produced from less fuel and other resources elsewhere in the life cycle.

Various sustainability issues associated with different parts of the natural gas power life cycle are discussed further in the following sections, in conjunction with the related indicators. The indicators are, where possible, expressed per kWh electricity generated in order to enable equivalent comparisons between gas and other electricity options.

5.3 Data sources and assumptions

The key assumptions and data sources for the natural gas option are discussed below. Full results are given in Appendix 3. Wherever possible and available, a range of values for each option has been considered to establish the lower and upper bounds. Where appropriate, average values are used in the sustainability assessment. In other cases, 'central' estimates are used instead, representing the most likely values for present and near-term new build, based on the specific technology type expected to be deployed.

5.3.1 Techno-economic data and assumptions

The indicators used for the techno-economic assessment are shown in Table 2. The data sources used are discussed below.

5.3.1.1 Operability

Capacity factor

The value used in the assessment is the average for UK CCGTs from 2005-2009 [16]. The upper and lower bounds are the extremes from that same time period. No data beyond 2009 were available.

Availability factor

The availability factor is calculated as the 2007-2009 average for CCGTs owned by Scottish and Southern Energy [261], as these are the only UK data available. The upper and lower bounds are the extremes from that same time period.

Technical and economic dispatchability

As for nuclear power, the data for technical dispatchability have been obtained by observing operator-specified information [95] over a period of several months; they are summarised in

Table 14. It should be noted that these figures may reflect the way in which operators choose to run their plants rather than the plants' technical abilities.

The data for economic dispatchability, estimated as a ratio of capital and total levelised costs, are based on the cost estimates described further below.

Table 14: Summary of technical dispatchability data for natural gas power retrieved from Balancing Mechanism Reporting System [95]

Ramp-up rate (%/min.)	worst	0.85
	average	1.63
	best	2.54
Ramp-down rate (%/min.)	worst	0.87
	average	2.47
	best	5.24
Minimum down-time (mins)	worst	600
	average	306.67
	best	30
Minimum up-time (mins)	worst	990
	average	410
	best	300

Lifetime of fuel reserves

The central estimate for the lifetime of fuel reserves reflects economically recoverable resources in 2010, as specified by BP [262]. The lower estimate assumes that economically recoverable reserves stay the same, but demand increases at a rate of 1.3% per year, as suggested by the EIA's International Energy Outlook 2010 reference case [263], resulting in faster use of reserves. The upper estimate reflects the total recoverable resource including unconventional gas (shale gas, coal-bed methane and 'tight' gas[24]) [264].

5.3.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

As discussed in Section 3.2.1.2, flexibility reflects the ability of a technology to provide trigeneration, net negative CO_2 emissions and high temperature (800°C) H_2 production. Ten

[24] Tight gas refers to natural gas found in formations with permeability below a certain threshold, the level of which is not universally established [264]. As a result of this low permeability, the gas cannot easily flow through rock, making extraction more difficult than would be the case for a conventional formation.

points are accrued for each of the three criteria, with the sum being squared and divided by operational lifetime. The data for natural gas power are shown in Table 15.

Table 15: Data on the technological lock-in resistance of natural gas power

Tri-generation	yes
Net negative CO_2 emissions	no
Thermochemical H_2 production	yes
Lock-in index score (0-30)	20
Lifetime (yrs)	25
Total score (f^2/l)	**16**

5.3.1.3 Immediacy

Time to plant start-up

The central estimate is the average construction time of all new CCGTs proposed in the UK by large utility companies (Drakelow D and E [259] and Willington C [239]). As this indicator measures time taken to start up the plant from the start of construction, the figures do not include planning and preliminary studies.

5.3.1.4 Levelised cost of generation

Capital, operational, fuel and total levelised costs

As for nuclear power, cost estimates considered here are based on those by Mott MacDonald [201] at 10% discount rate. They therefore inherit most of the assumptions made there, such as plant lifespan and average capacity factor. However, these assumptions are broadly in line with those used in the rest of the assessment in this work. Any subsidies are excluded from these costs, including the carbon price applied by Mott MacDonald. The cost data are summarised in Appendix 3. As mentioned in Section 4.3.1.4, the values used in this study have been verified against earlier UK cost estimates [118, 202] as well as data for other OECD countries published by IEA [99, 113] and MIT [119], but these data are not included due to obsolescence and inappropriate country-specificity.

5.3.1.5 Cost variability

Fuel price sensitivity

This indicator has been estimated using the fuel cost data and total levelised generation costs discussed in the previous section.

5.3.1.6 Financial incentives

Financial incentives and assistance

This indicator includes revenues that are available from the Renewables Obligation, the FiT and an estimate of the carbon tax avoided by 'zero-carbon' (at the point of generation) technologies. Gas power in the UK does not receive any of these incentives, giving a value of zero as shown in Table 16.

Table 16: Financial incentives for natural gas power

Number of ROCs received per MWh	0
Value per ROC 2011/12 (£)	n/a[a]
Total ROC incentive (£/MWh)	*n/a*
Value of FiT for <4 kWp in 2011/12	
new build £/MWh)	n/a
retrofit (£/MWh)	n/a
Total average FiT incentive (£/MWh)	*n/a*
Avoided emissions relative to CCGT (t CO_2/MWh)	0
Total avoided carbon price[b] (£/MWh)	*0*
TOTAL (£/MWh)	**0**

[a]n/a: not applicable
[b]Average carbon price from April 2010 to March 2011: £12.69/t CO2 [203]

5.3.2 Environmental data and assumptions

The indicators used for the environmental assessment are shown in Table 2. The key assumptions and data sources are summarised below.

5.3.2.1 Material recyclability

Recyclability of input materials

Material recyclability is the percentage of materials used for construction of a power plant that can potentially be recycled. For most construction materials, the potential recyclability is 100%. The exceptions to this are rock wool, which is assumed to be 97% recyclable [265], and concrete, which is calculated to be 79.4% recyclable [based on 204][25]. Recyclability is calculated using the amounts of construction materials given in Ecoinvent [204], as illustrated in Table 17. A plant

[25] Concrete is typically crushed into aggregate, which may then be used to manufacture new concrete by adding new cement. In the Ecoinvent v2.2 database [204] concrete contains 1890 kg of aggregate per 2380 kg concrete (= 79.4%).

capacity of 400 MW is described in the Ecoinvent database; this is in good agreement with new build proposals in the UK, with larger plants simply combining several ~400 MW units in modular fashion (see, for example, West Burton CCGT [112] and Willington C CCGT [260]).

The value in Table 17 (89.3%) has therefore been selected as the central estimate for the recyclability of CCGTs. The lower bound (79.4%) corresponds to the amount of material that would be recycled at current UK demolition rates (see Section 4.3.2.2, Table 9).

Table 17: Major materials used for plant construction and their end-of-life recyclability for a 400 MW combined cycle natural gas turbine (CCGT) [204]

Material	Amount (t)	Recyclability (%)
Reinforcing steel	8,800	100
Chromium steel 18/8	1,800	100
Low-density polyethylene	1,300	100
Chromium	0.976	100
Copper	440	100
Nickel	6.3	100
Cobalt	0.72	100
Aluminium	440	100
Ceramic tiles	4.2	100
Rock wool	660	97
Concrete	14,280	79.4
Total materials	*27,732*	
Total recyclability of the plant		**89.3% (24,772 t)**

5.3.2.2 Other environmental issues

Environmental (LCA) impacts

The data for natural gas have been adapted from the CCGT model in the Ecoinvent v2.2 database [204], a model representative of a modern, 58% efficient plant (net calorific value basis). The size of the plant is 400 MW, also representative of new build as discussed above. The model was adapted to match UK conditions as follows:

- the current UK electricity mix is used for all relevant life cycle stages carried out it the UK;
- 90% of gas supplied to the plant is assumed to originate from the North Sea;
- the remaining 10% of gas supplied to the plant is from LNG, using an existing dataset describing LNG produced and liquefied in Algeria then shipped to Japan and regasified. The original oceanic shipping distance of 7600 km is retained as an approximate value for international LNG imports to the UK; further refinement of this value was not considered beneficial due to the rapidly changing LNG import mix.

Following modelling of the CCGT life cycle as described above, sensitivity analyses were carried out to estimate the lower and upper bounds for the environmental impacts. As part of these analyses, the effect of end-of-life recycling of all major components was explored using current UK demolition recycling rates, as described in Section 4.3.2.2 (see Table 9). This contrasts with the assumption used in the central estimate in which end-of-life recycling is not considered.

Additional sensitivity analysis included varying the proportion of LNG in the fuel mix from 0-100% in order to explore the likely repercussions of the UK relying more heavily on LNG as North Sea yields continue to decline.

<u>Greenfield land use</u>
This indicator is based on visual inspection, via Google Maps [215], of the land plots of the three proposals mentioned in Section 5.3.1.3 (Drakelow D and E and Willington C). All sites are brownfield.

5.3.3 Social data and assumptions

The indicators used for the social assessment are shown in Table 2. The data sources used are discussed below.

5.3.3.1 Provision of employment

<u>Direct and total (including indirect) employment</u>
To enable comparison with nuclear and other technologies, wherever applicable the same data sources have been used for natural gas. Thus, employment related to the extraction of ores and aggregates (for manufacture of concrete, steel and other metals) has been calculated based on material requirements specified in Ecoinvent [204] and employment data from BHP Billiton [216] and the Mineral Products Association [217]. The processing of raw materials into metals is based on labour data from Corus [218].

Construction figures have been derived from the job requirements and schedule of the proposed 2000 MW Willington C CCGT plant [260]. The operational stage is based on the jobs required to operate, maintain and support three CCGTs owned by RWE npower plc. (Didcot B, Great Yarmouth and Little Barford) together with their respective capacities (1360, 400 and 680 MW, respectively) [266]. These plants have been chosen as they provide the most comprehensive dataset of operating UK plants. As is the case for all technologies assessed in this research, maintenance employment only includes inspection and installation of replacement parts; employment owing to the manufacture of parts is excluded. Due to a lack of available estimates in the literature, employment during decommissioning is assumed to be 20% of construction employment. This is based on the approximate ratio of decommissioning cost to construction cost (see Section 4.3.3.1), and the same assumption has been maintained across all technologies assessed in this work for consistency. However, gas power plants are expected to have lower decommissioning costs than, for example, nuclear plants [99], so this may be an overestimate.

Regarding employment due to extraction of natural gas, data have been derived from economic reports covering the years 2005-2009 by Oil & Gas UK [267-271]. The results were then averaged for that time period. No data were available beyond 2009. Because the majority of gas platforms also produce oil, employment was allocated to gas based on the economic value of the products, taken from the same Oil & Gas UK reports (average gas price over reported period = £0.163/m^3; average oil price = £43.8/barrel). Employment figures for this stage include employees and contractors working on gas rigs as well as supporting staff.

Note that the aforementioned stages together form the total employment estimate. Direct employment is then estimated using the employment figures for the construction, operation and decommissioning stages.

5.3.3.2 Human health impacts

<u>Worker injuries</u>

The worker injury results are directly linked to the employment results in that the number of person-years of employment for each life cycle stage is used to calculate the number of expected injuries using Health and Safety Executive data [151] appropriate for the respective type of labour, as shown in Table 18.

Table 18: Injury rates used to calculate worker injuries in the natural gas life cycle [151]

Life cycle stage	HSE sector-specific injury rate used	Number of injuries per 100,000 workers
Extraction of natural gas	Extractive and utility supply (total)	1,117.1
Manufacture of plant components		
Extraction of ores/aggregates	Other mining	859.6
Processing	Manufacturing (total)	811.8
Manufacture of components	Manufacturing (total)	811.8
Construction	Construction (total)	777.2
Operation	Electricity, gas, steam and hot water supply (total)	553.8
Decommissioning	Construction (total)	777.2

<u>Human toxicity potential & Human health impacts from radiation</u>

These two impacts are estimated as part of life cycle assessment (see Section 5.3.2.2).

5.3.3.3 Large accident risk

<u>Fatalities due to large accidents</u>

As is the case for nuclear power, large accident fatalities are based on data from the Paul Scherrer Institut [221] drawing on previous work using their historical Energy-Related Severe Accident Database (ENSAD) [222, 223]. ENSAD defines large accidents as those causing at least five fatalities. These results represent current Swiss conditions, but are likely to be equally appropriate for the UK: the location of the power plant is not particularly relevant in this case, as less than 20% of accidents in the natural gas energy chain occur at the point of power production, with the critical points being transportation and distribution [222].

5.3.3.4 Local community impacts & Human rights and corruption

These impacts have not been considered, as they are company-specific and therefore cannot be assessed at the generic technology level.

5.3.3.5 Energy security

<u>Avoidance of fossil fuel imports & Fuel supply diversity</u>

The amount of imported fossil fuel potentially avoided is calculated from the average efficiency of the current UK fossil fuel fleet [calculated from 16] on the basis that a unit of electricity generated by non-fossil capacity displaces a unit generated by fossil capacity. This is described further in Section 3.2.3.6 as is the methodology of the diversity of fuel supply indicator, which has been calculated using 2009 UK data [16], as shown in Table 19. Results for earlier years have also been calculated using data from the same source [16], as have results for the USA by way of comparison using data from the US Energy Information Administration [272]. These are discussed further in the results section (5.4.3.5).

Table 19: UK gas supply in 2009 [16] and the resulting fuel supply diversity index

	Supply (GWh)	**Percentage of supply (%)**
Net imports	427,186	31.47 (*a*)
Netherlands	*56,435*	*13.21*
Norway (including LNG)	*262,034*	*61.34*
Algeria (LNG)	*19,392*	*4.54*
Australia (LNG)	*812*	*0.19*
Egypt (LNG)	*5,804*	*1.36*
Qatar (LNG)	*61,159*	*14.32*
Trinidad and Tobago (LNG)	*20,766*	*4.86*
USA (LNG)	*784*	*0.18*
Simpson Diversity Index of net import mix	**0.587** (*b*)	
UK natural gas production	693,966	68.53 (*c*)
Total fuel supply diversity index (= $c + ab$)	**87.00**	

Fuel storage capabilities

Fuel storage capabilities are based on five year average net calorific value data for fuel imported to the UK [16].

5.3.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

This indicator is not applicable to the natural gas life cycle (for further description see Section 3.2.3.7). Natural gas is assigned a score of zero.

5.3.3.7 Intergenerational equity

Abiotic resources (elements and fossil fuels)

These indicators have been estimated as part of LCA (see Section 5.3.2.2).

Volume of radioactive waste and liquid CO_2 for storage

This indicator is currently not applicable to the natural gas life cycle, as no CCGTs have been proposed in the UK with carbon capture and storage facilities (for further description of this indicator, see Section 3.2.3.8). Thus natural gas has been assigned a score of zero.

5.4 Results and discussion

This section presents the assessment results for the natural gas (CCGT) option. The summary results are shown in Figure 11, Figure 12 and Figure 13; full results can be found in Appendix 3.

5.4.1 Techno-economic sustainability

This sub-section addresses the techno-economic part of the sustainability assessment of natural gas power. The results are presented in Figure 11 and discussed below.

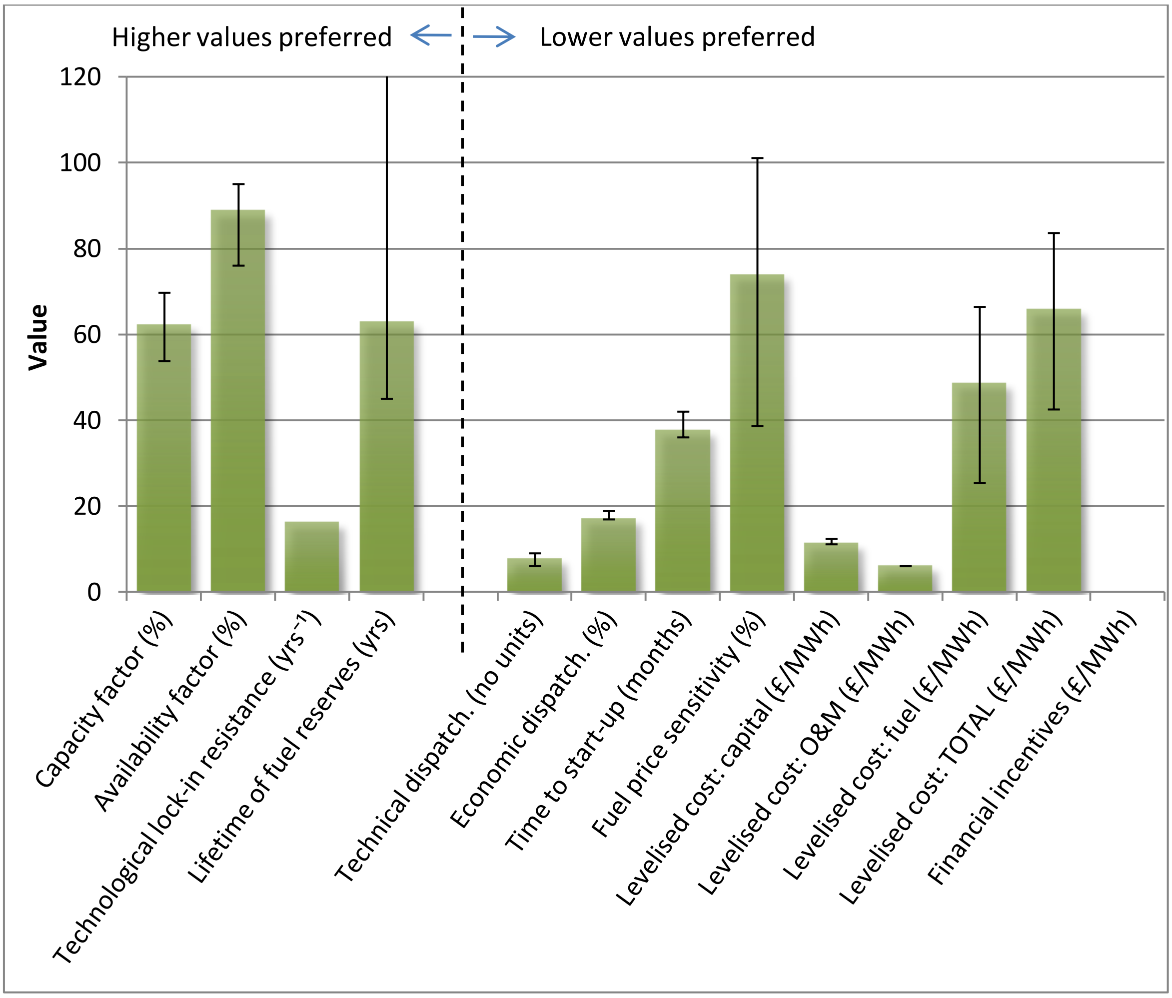


Figure 11: Techno-economic sustainability of gas power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases. The upper value of the estimate for *lifetime of fuel reserves* is 250 years. For full results, see Appendix 3.

5.4.1.1 Operability

Capacity and availability factors

Higher availability potentially allows higher capacity factors, effectively reducing the cost (as well as social and environmental impacts) by producing more energy from the same fixed resources. As shown in Figure 11, gas power has an availability factor of around 89% (ranging from 76-95%) and a capacity factor of roughly 62% (54-70%). Clearly there is a significant difference between these figures, reflecting the fact that gas plants are typically used partially to load-follow, meaning they reduce output or shut down overnight when demand for electricity is low. This is an economic choice resulting from their high marginal cost of operation (see Section 5.4.1.4). As a result, improving reliability (and thus availability) is unlikely to significantly influence capacity factors: profitability depends more upon the cost of fuel and the price of electricity sold to the grid than on the reliability of the plant.

Technical and economic dispatchability

As mentioned above, CCGTs have high marginal costs due to the cost of gas (also see Section 5.4.1.4): as shown in Figure 11, their capital costs only comprise around 17% of total costs (in a range of 16.9-18.9%), with the remainder mainly being variable costs. Consequently, it is more economic to follow load with a CCGT than it is to provide baseload. In other words, economic dispatchability is high.

This economic preponderance to load-follow is generally matched by technical ability, as shown in Table 14 (see Section 5.3.1.1): minimum down times, for example, were observed to be as low as 30 minutes, meaning plants were shut down and restarted within a 30 minute period. The equivalent value for nuclear power was 999 minutes (the maximum value recorded by the Balancing Mechanism Reporting System; Table 5), reflecting the fact that nuclear plants cannot be restarted quickly after being fully shut down. The total summed rank for CCGTs was 7.67, varying from 6 to 9, which compares to a central estimate of 11.67 for nuclear power (lower values being preferable). There are, however, extra maintenance costs associated with varying load regularly in a CCGT due to increased thermal stress [273].

Overall, CCGTs are better placed to follow load than many other options, particularly nuclear, wind and photovoltaics. As a result, they might be expected to do this more in the future to compensate for the increasing penetration of these less dispatchable options.

Lifetime of global fuel reserves

At 63 years, the lifetime of global natural gas reserves is the shortest of the main fuels (coal, gas and uranium). This is particularly relevant to the UK which, as discussed in Section 5.2, has seen indigenous production decline markedly in the last decade. The result of this will be increased exposure to global markets that, in turn, can be expected to become more volatile as reserves decline and demand increases. There is, however, the increasingly economic possibility of extracting ‘unconventional’ gas such as coal-bed methane and shale gas which could raise global reserves to around 250 years. These sources, however, remain controversial due to various environmental and social including pollution, earthquakes and climate change.

5.4.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

This indicator is an estimate of how well each option caters for potential changes in the way that energy is used nationally, accounting for whether it could be modified to tri-generate electricity, heating and cooling, to have negative global warming potential (e.g. integrated biomass and CCS) or to produce hydrogen at high temperatures. As discussed in Section 3.2.1.2, CCGTs are very resistant to technological lock-in due to their relatively short lifetime (typically 25 years [112]) and high temperature of over 1250°C [273]. The overall score is 16, which compares to 1.67 for nuclear power (see Section 4.4.1.2).

5.4.1.3 Immediacy

Time to start up

CCGTs typically require only 36-42 months to construct, even for large capacity (>1000 MW) plants (central estimate = 37.5 months). Such a short time to start-up is desirable as it reduces the payback period and the risk associated with the construction phase.

5.4.1.4 Levelised cost of generation

Capital, operational, fuel and total costs

The costs shown in Figure 11 represent the market cost of electricity generation excluding incentives provided by market mechanisms, which are discussed in Section 5.4.1.6. They are not, therefore, the net costs paid by owners. At 10% discount rate, the natural gas option costs 4.3-8.4 pence/kWh with a central estimate of 6.6 pence/kWh. This is cheaper than nuclear power (6.7-9.9 pence/kWh with a central estimate of 9.5; see Section 4.4.1.4). However, the cost profile is antithetical to that of nuclear power: only 17% of the total levelised cost is due to capital, while fuel contributes around 74%. This low capital cost corresponds with a low investment risk, meaning that a potential investor may well assess the natural gas option at a lower discount rate than, for example, nuclear power, decreasing its apparent cost. However, as the majority of the cost of gas power is spread across the life of the plant (rather than the construction period), changing the discount rate has only a modest effect: for instance, reducing the discount rate from 10% to 5% will only decrease the apparent cost by less than 10%. This contrasts with the effect on a capital-intensive option such as nuclear power, for which the total cost will reduce by over 60% (calculated from [99]; see Section 4.4.1.4).

Moreover, the low capital risk associated with gas power comes at the expense of very high variable costs (fuel and variable maintenance) which, given the recent volatility of gas prices creates an extremely variable total cost (see Section 5.3.1.5 below).

5.4.1.5 Cost variability

<u>Fuel price sensitivity</u>

Fuel prices are the major component of future cost uncertainty. This is a significant problem for CCGTs, for which approximately 74% of total levelised cost is due to fuel. This becomes particularly important as fuel reserves decrease and demand increases greatly due to developing countries like China and India. If gas prices were to increase significantly over the life of a fuel price-sensitive asset like a CCGT, the owner would likely be forced to operate the plant at progressively lower capacity factors, requiring replacement capacity to make up the shortfall in output.

5.4.1.6 Financial incentives

<u>Financial incentives and assistance</u>

The quantification and results for this indicator are discussed in Section 5.3.1.6 (see Table 16). However, gas power currently receives no incentives. It is in fact penalised by the carbon price of the EU Emissions Trading Scheme, although this currently has a very limited effect on its financial viability: as shown in Table 16, the 2010/2011 average carbon price was £12.69/tCO_2 [203], which amounts to a penalty of around 0.5 p/kWh for a CCGT emitting 400 g CO_2/kWh. The Government has proposed to raise the carbon price, introducing a floor of £16/tCO_2 in 2013, increasing to £30/tCO_2 by 2020 [28]. At £30/tCO_2, the penalty for a CCGT becomes 1.2 p/kWh (= 0.0004 tCO_2/kWh × £30) which, based on the levelised cost estimates discussed in Section 5.4.1.4, adds around 18% to the total cost of electricity from natural gas. The significance of this cost penalty is arguably low given the fact the natural gas power is relatively cheap at present.

5.4.2 Environmental sustainability

This sub-section addresses the environmental part of the sustainability assessment of electricity from natural gas. All environmental indicators, except for material recyclability and greenfield land use, have been estimated using life cycle assessment (LCA) and the CML 2001 impact assessment methodology (the November 2009 update) [59, 139]. GaBi v4.4 LCA software [244] and the Ecoinvent v2.2 database [204] have been used for these purposes. All estimates are based on modelling undertaken in this study. The results are presented in Figure 12 and discussed below.

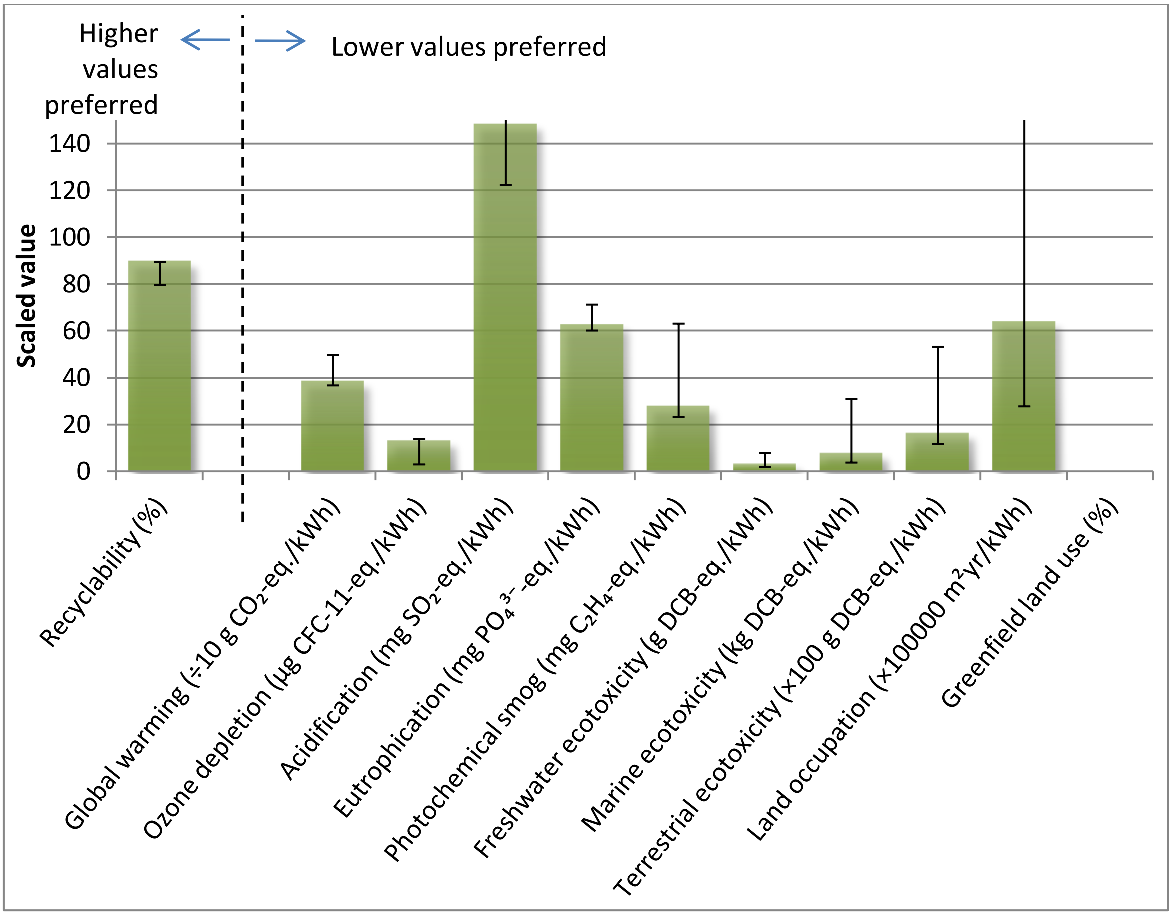


Figure 12: Environmental sustainability of gas power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled by multiplying or dividing their original values by the factors shown in brackets. Bar height represents the central estimate in all cases. The upper value of the estimate for *acidification* is 370 µg SO_2-eq./kWh. The upper value of the estimate for *land occupation* is 3.79 $\times 10^{-3}$ m^2yr (379 on the graph's scaled *y* axis). For full results, see Appendix 3.

5.4.2.1 Material recyclability

Recyclability of input materials

Figure 12 (and Table 17 in Section 5.3.2.1) shows that the potential recycling rate of a CCGT power plant is around 89%, which is limited mainly by the 14,000 tonnes of concrete required (for a 400 MW plant).

At current UK recycling rates (see Section 4.3.2.2, Table 9), the proportion of a CCGT plant expected to be recycled is 79%. Results from the natural gas sensitivity analysis show that recycling plant components at current UK rates has a positive effect on some life cycle environmental impacts, as shown in Table 20. The majority of the environmental impacts remain virtually unchanged because they result from emissions associated with sourcing, transporting and burning gas. The exceptions are freshwater and marine eco-toxicity which are decreased by 14.24% and 19.16%, respectively. These reductions are due to the fact that the construction stage of the life cycle accounts for 31% of the freshwater impact and 23% of the marine impact, mainly due to heavy metal emissions during the steel and copper production chains. Consequently, recycling metal components significantly mitigates the impacts.

Table 20: Percentage reduction in impacts due to recycling of CCGT components at end-of-life, using current UK recycling rates

Impact	Reduction of impact at current UK recycling rates[a] relative to no recycling (%)
Global warming potential	0.05
Ozone depletion potential	0.05
Acidification potential	0.95
Eutrophication potential	2.14
Photochemical smog potential	0.76
Freshwater eco-toxicity potential	14.24
Marine eco-toxicity potential	19.16
Terrestrial eco-toxicity potential	0.29

[a] Aluminium 95%, other metals 99%, plastics 26%, concrete 71.5%, fibre cement facing tile 0%, paper 69%, gravel 30%, glass fibre reinforced plastic 10%, ceramic tiles 64%, insulation 18%, glass 0% (see Section 4.3.2.2).

5.4.2.2 Global warming potential (GWP)

As shown in Figure 12, the central estimate obtained in this work for the GWP of gas power is 379 g CO_2 eq./kWh. This is similar to other estimates for CCGTs in literature: for example, 426 g CO_2 eq./kWh (PSI [246]); 400 g CO_2 eq./kWh (Viebahn et al. [274]). The lower value in the present study is due to the relatively high efficiency assumed as well as the proximity of the UK to North Sea gas, which reduces transport distances. 93% of the total GWP is due to the operational stage of the life cycle.

The estimated GWP of natural gas power is lower than the current average UK electricity value of 584 g CO_2 eq./kWh [204]. However, greenhouse gas emissions from CCGTs are likely to worsen in the future as LNG use continues to increase and indigenous production continues to decline: using 100% LNG gives a figure of 496 g CO_2 eq./kWh compared to 366 g CO_2 eq./kWh using only traditional North Sea and European piped gas. These figures respectively form the upper and lower bounds shown in Figure 12. Indeed, if full life cycle emissions of GHGs were used in legislation (as opposed to direct emissions, as is the case currently), the upcoming Emissions Performance Standard (EPS) [28] would preclude the building of CCGTs for which LNG contributed more than 65% of the natural gas supply - the EPS enforces a limit of 450 g CO_2/kWh which is breached beyond this level of LNG use.

5.4.2.3 Ozone layer depletion potential (ODP)

Natural gas power has an ODP of 12.6 μg CFC-11 eq./kWh in the central case: around 23 higher than the value for nuclear power discussed in Section 4.4.2.3. This is a result of halogenated gases used as fire retardants in gas pipelines and would therefore be mitigated to an extent by switching from traditional gas to LNG: if no LNG is used, the result is as high as 13.8 μg CFC-11 eq./kWh, but if the supply mix is 100% LNG, the result falls to 2.8 μg CFC-11 eq./kWh. This introduces a conflict with the GWP discussed above: to reduce ODP, greater usage of LNG is preferable, but using 100% LNG would increase global warming potential by nearly 30%.

5.4.2.4 Acidification potential (AP)

AP is estimated at 0.148 g SO_2 eq./kWh (within a range of 0.122-0.370). By far the biggest contributor to this impact (99.2%) is the emission of sulphur dioxide and nitrogen oxides during extraction, transportation and combustion of the gas, with 56% due to the latter.

5.4.2.5 Eutrophication potential (EP)

The biggest single contributor (39%) to the total EP of 0.062 g PO_4^{3-} eq./kWh is emissions to sea water during the gas extraction stage. The range of values obtained through sensitivity analysis spans 0.060-0.071 g PO_4^{3-} eq./kWh, with the higher value caused by 100% LNG use.

5.4.2.6 Photochemical oxidant creation potential (POCP)

POCP is estimated to range from 0.023-0.63 g C_2H_4 eq./kWh with a central estimate of 0.027. Around 60% of this impact is due to emission of non-methane volatile organic compounds, mostly during gas combustion.

5.4.2.7 Water eco-toxicity

Freshwater eco-toxicity potential (FAETP)

Natural gas power has an estimated FAETP of 2.6 g DCB eq./kWh. Over 97% of this impact is due to emissions of heavy metals to freshwater throughout the life cycle. The range of values obtained spans 1.7-7.7 g DCB eq./kWh, with the higher value reflecting the increased impact of LNG use which is mainly (69%) due to emissions of nickel and vanadium, particularly from production of pipelines and oceanic transport vessels.

Marine eco-toxicity potential (MAETP)

The MAETP of 7.1 kg DCB eq./kWh is mainly due to the extraction of natural gas, with 72% of the impact attributable to this stage of the life cycle. However, this is a low figure, comparing to around 40 kg for nuclear power (see Section 4.4.2.7). In the worst case (100% LNG use) the result for natural gas increases to 31 kg due to emission to air of hydrogen fluoride during oceanic transportation, and in the best case (end-of-life recycling and zero LNG use) is as low as 3.6 g.

5.4.2.8 Land use and quality

Terrestrial eco-toxicity potential (TETP)

The terrestrial eco-toxicity result is 0.16 g DCB eq./kWh and, as shown in Figure 12, this lies within a potential range of 0.12-0.53. In the central case, 40% of the impact is due to the emission of chromium during the stainless steel production chain associated with power plant components.

Land occupation

Over the whole life cycle, generating electricity from natural gas requires approximately 0.00063 m^2yr/kWh, which is comparable to the nuclear life cycle result of 0.00055 m^2yr/kWh (see Section 4.4.2.8). Only around 6% of this area is the power plant itself, with the remainder primarily being gas pipelines and associated facilities. Since more facilities are needed throughout the life cycle if LNG is used, a maximum value of 0.00379 m^2yr/kWh can be achieved if all fuel is in the form of LNG. Using no LNG, together with end-of-life recycling of the CCGT itself, reduces the figure to 0.00028 m^2yr/kWh.

Greenfield land use

The greenfield land use indicator is intended to describe the percentage of new power plants likely to be built on greenfield land and as such only the operational stage is considered. Of the three sites currently being proposed by large UK utility companies, all are on brownfield sites, giving a score of 0% (see Figure 12).

5.4.3 Social sustainability

This sub-section addresses the social part of the sustainability assessment of natural gas power. The results are presented in Figure 13 and discussed below.

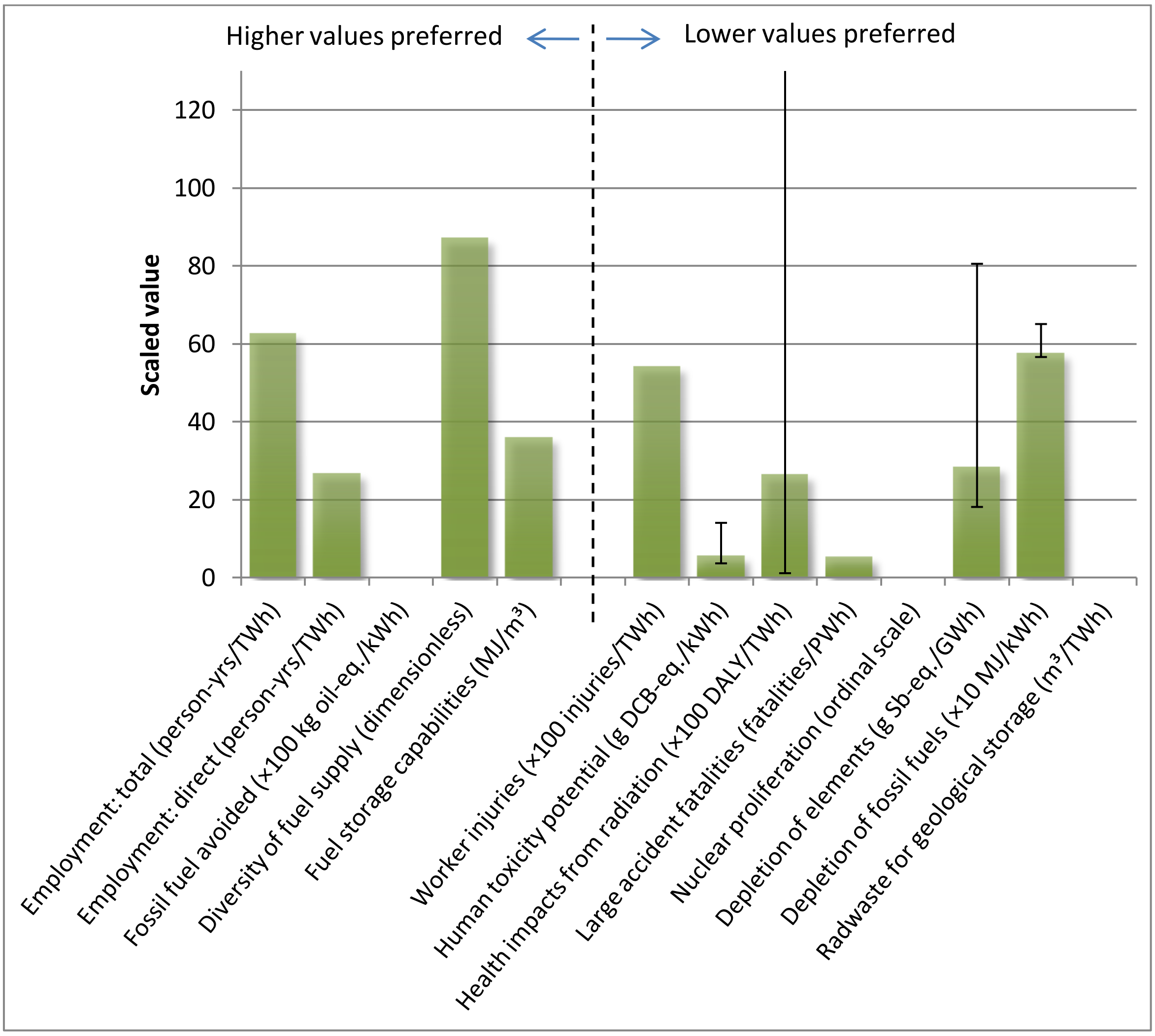


Figure 13: Social sustainability of gas power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled by multiplying or dividing their original values by the factors shown in brackets. Bar height represents the central estimate in all cases. The upper bound for *health impacts from radiation* is 2.53 DALYs/TWh (253 on the graph's scaled *y* axis). For full results, see Appendix 3.

5.4.3.1 Provision of employment

<u>Total employment</u>

Total employment estimates in Figure 13 comprise direct and indirect employment. As mentioned in Section 3.2.3.1, the former is related to the power plant erection, operation, maintenance and decommissioning while the latter refers to jobs in fuel extraction and production, waste management and other services to the plant over its lifetime. The results show that natural gas power provides 62 person-years/TWh of total employment, just under half of which is direct (i.e. specifically related to the power plant site). As discussed in Section 4.4.3.1, a twin-reactor nuclear plant would employ around 800 people during its operation [147]: a CCGT of the same capacity (2.7 GW) would only employ 200-300 [calculated from 147, 266]. Approximately 41% of the total employment created by natural gas power is due to the extraction of natural gas although, as discussed in Section 5.3.3.1, due to a lack of specific data the result for this stage is based on economic allocation between employment at oil and gas-producing platforms.

Direct employment

When indirect employment is excluded from the total, natural gas power provides 26.6 person-years/TWh, 60% of which is due to the operational stage discussed above.

5.4.3.2 Human health impacts

Worker injuries

About 0.54 injuries are incurred for every TWh of electricity generated by natural gas (Figure 13). This is very similar to the nuclear life cycle, estimated at 0.6 (Section 4.4.3.2). As shown in Table 18 (see Section 5.3.3.2) injury rates are relatively high in the extractive sector; since the gas extraction stage provides 41% of total employment, this increases the number of injuries attributable to the life cycle. As a result, gas and nuclear injury rates are almost identical despite the nuclear life cycle providing 30% more employment.

Human toxicity potential (HTP), excluding radiation

Power from natural gas has an HTP of 5.4 g DCB eq./kWh in the central case, ranging from 3.7-14.1 depending primarily on the proportion of LNG used. This compares to 115 g for the nuclear life cycle.

Total human health impacts from radiation

The health impact of radiation from the natural gas life cycle is 0.26 disability-adjusted life years (DALYs) per TWh (Figure 13), mainly due to the contribution of nuclear power to the electricity used throughout the life cycle. The nuclear life cycle itself causes 20.3 DALY/TWh (see Section 4.4.3.2).

5.4.3.3 Large accident risk

Fatalities due to large accidents

The Paul Scherrer Institut estimate that a present-day CCGT and its associated energy chain causes 5 fatalities/PWh [221]. Despite the maximum number of fatalities caused by a single historical incident being relatively low at 109 [221], the high frequency of accidents gives gas power a fatality rate about 4000 times higher than the estimate for a new nuclear power station: as discussed in Section 4.4.3.3, despite a single incident potentially causing 49,000 deaths, the rate of accidents for a generation III nuclear power plant (such as the AREVA EPR) is estimated to be so low that only 0.0012 deaths occur per PWh generated [221].

5.4.3.4 Local community impacts and human rights & corruption

As mentioned in Section 5.3.3.4, these impacts have not been considered because they are company-specific and therefore not applicable for technology assessment. For further discussion, see Section 3.2.3.

5.4.3.5 Energy security

Avoidance of fossil fuel imports

As a fossil fuel option, gas power does not avoid fossil fuel imports. Therefore its score is zero.

Diversity of fuel supply mix

This indicator reflects the resilience of national electricity production to fuel supply disruptions, whether they are economic, technical or political. The diversity of fuel supply score for the UK natural gas supply mix is 0.87 (= 0.6853 + (0.3147 × 0.587); see Section 5.3.3.5). This is a relatively high score, reflecting the fact that a good proportion (69%) of UK gas supply is still produced indigenously and the import mix is now quite diverse owing to an increase in global LNG trading. Data from earlier years [see 16] show less LNG trade and, as a result, a less diverse import mix. However, UK production in those years was stronger than in the present, resulting in better overall scores prior to 2008, as shown in Figure 14. Also shown in the figure is the fact that the UK's gas supply diversity fell below that of the USA in 2008 for the first time and has not yet recovered. This illustrates the fact that, as indigenous gas yields continue to decline, the UK will have to continue its switch to global LNG trade in order to maintain security of supply.

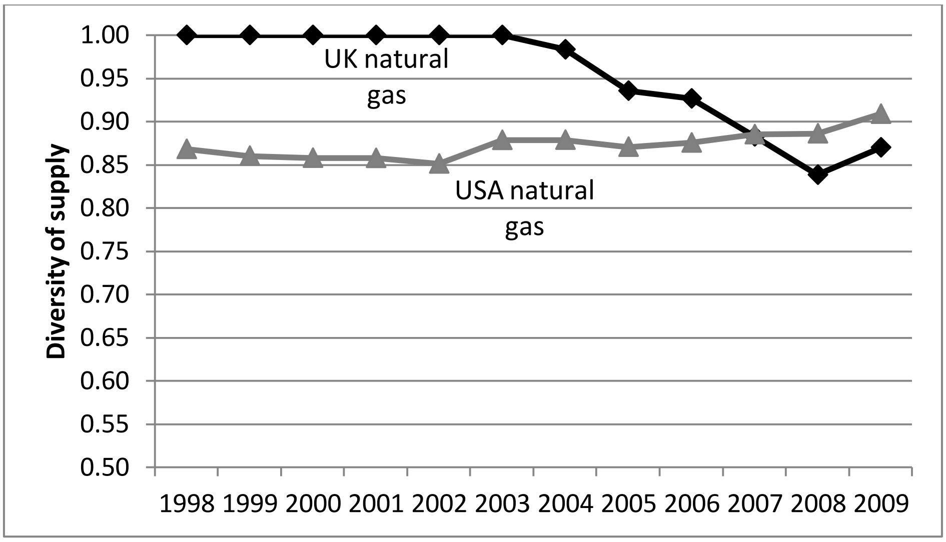


Figure 14: Historical results illustrating the diversity of UK and USA natural gas supplies

Fuel storage capabilities

This indicator shows inherent resilience: energy dense fuels are physically easier to transport and store to be used when supply is problematic. Gas has a low energy density of 0.035 GJ/m^3 [calculated from 275]), making stockpiling difficult. With current storage capacity and assuming average demand, the UK has just under 17 days' supply of natural gas stockpiled [calculated from 276, 277] (although this is set to increase over the next decade [278]). In contrast, 287 million times more energy could be stored in the same area in the form of PWR fuel assemblies (assuming burn-up of 50 GWd/tU). As a result of the low energy density of gas, disruptions in the supply chain can leave the country vulnerable to supply shortages. A recent example of such a situation was the 2005-2006 Ukraine/Russia gas dispute which, although the majority of UK gas imports are in fact from Norway [276], highlighted the security of supply issues associated with fuel imports. On the other hand, most renewables do not require fuel (apart from biomass) and are therefore not subject to supply disruptions (although they may produce energy intermittently).

5.4.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

This is not an applicable indicator in the case of natural gas. Therefore, gas has been given a score of zero.

5.4.3.7 Intergenerational equity

Use of abiotic resources (elements)

As indicated in Figure 13, use of abiotic elements in the natural gas life cycle totals 28.3 g Sb eq./GWh. Around two thirds (68%) of this impact is due to the use of chromium, copper, lead, molybdenum and nickel throughout the life cycle, primarily during manufacture of the plant and transportation pipelines. As a result, recycling the plant at end-of-life yields a lower impact of 18.2 g Sb eq./GWh. Conversely, due to the additional facilities and infrastructure needed in the LNG life cycle, using only LNG as fuel gives a result of 80.6 g Sb eq./GWh.

Use of abiotic resources (fossil)

Fossil resource depletion in the natural gas life cycle is 5.75 MJ/kWh in the central estimate, ranging from 5.66-6.51 depending on the proportion of LNG used. The vast majority of this is due to the natural gas itself used in the power plant.

Volume of radioactive waste and liquid CO_2 to be stored

Natural gas power does not produce radioactive waste or liquid CO_2 for storage, and at the time of writing no CCGT power plants with carbon capture and storage have been proposed. Therefore, natural gas is given a score of zero.

5.5 Data quality in the natural gas power assessment

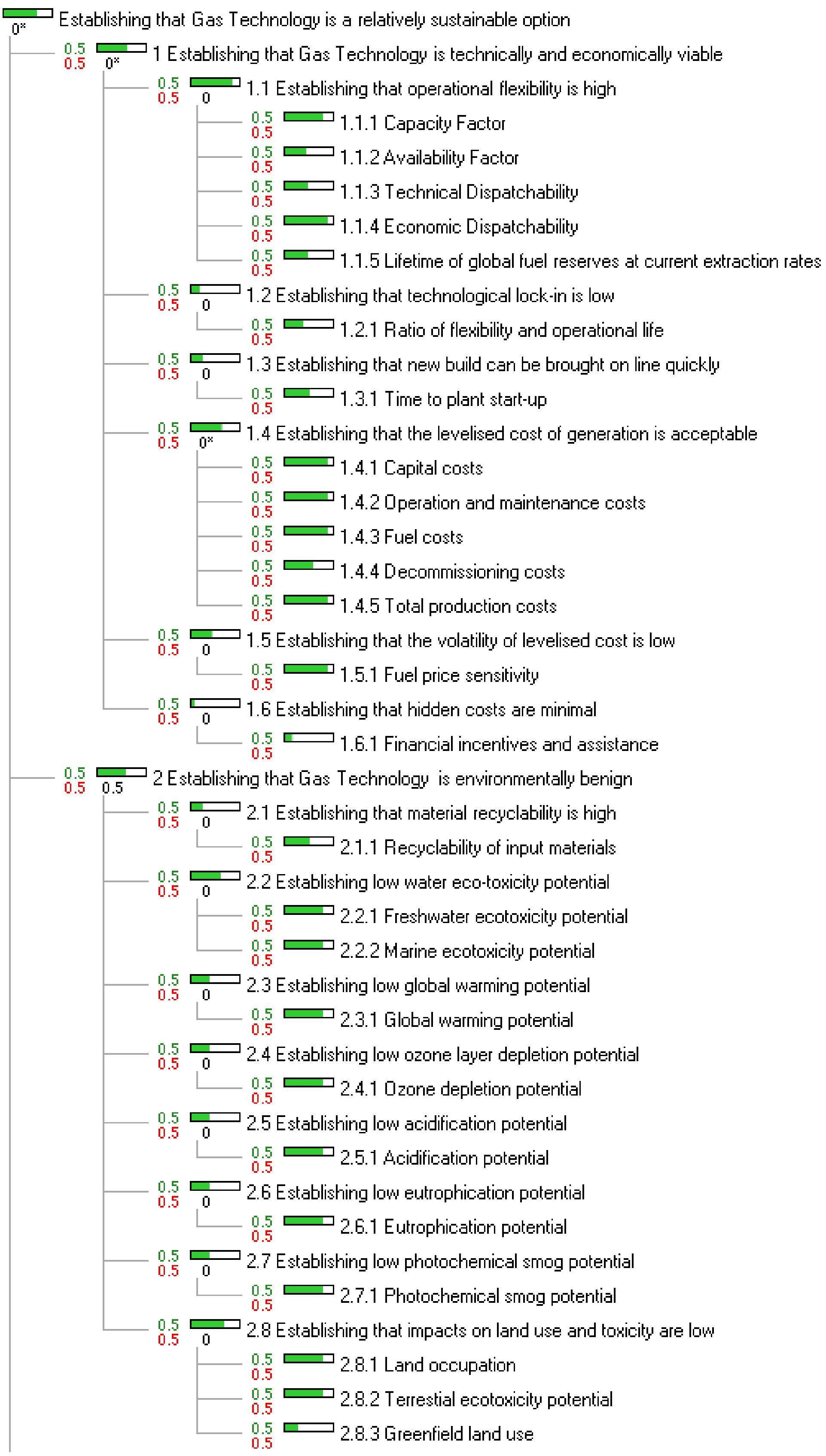
Data quality has been assessed using the same methodology as for the nuclear option and the other options assessed in this work (see Section 4.5 and Appendix 4).

Figure 15 shows a summary of the data quality analysis. The overall assessment is rated at 68% (where a rating of 100% would indicate perfect quality). This is close to the estimate for nuclear power (66%) and for similar reasons.

The weakest of the three 'pillars' in this sustainability assessment is the environmental group, scoring 60.4%. The only weaknesses in the data involve some uncertainty in construction requirements and emissions within the Ecoinvent dataset, as well as some approximation in the representation of LNG use as discussed in Section 5.3.2.2. However, as is the case for nuclear power (see Section 4.5), the main reason the environmental group scores lower than the others is simply the fact that most environmental indicators are derived from LCA and share the same data sources.

Overall, the data quality of the natural gas sustainability assessment is thought to be good considering the purposes of this study: that is, an assessment of a generic CCGT as might be built in the UK. Improvements could be made by focusing on lower rated areas shown in Figure 15 as shorter green bars. Thus, the focal points of potential future work would primarily be:

- improving the environmental group by expanding the treatment of LNG production and transportation to encompass more producing countries and better represent the UK import mix;
- improving the assessment of financial incentives and assistance by extending the current data to include hidden subsidies as discussed in Section 3.2.1.6; and
- improving the employment estimate using specific figures for the natural gas extraction phase, thereby avoiding the economic allocation of employment as discussed in Section 5.3.3.1.


Establishing that Gas Technology is a relatively sustainable option
1 Establishing that Gas Technology is technically and economically viable
1.1 Establishing that operational flexibility is high
1.1.1 Capacity Factor
1.1.2 Availability Factor
1.1.3 Technical Dispatchability
1.1.4 Economic Dispatchability
1.1.5 Lifetime of global fuel reserves at current extraction rates
1.2 Establishing that technological lock-in is low
1.2.1 Ratio of flexibility and operational life
1.3 Establishing that new build can be brought on line quickly
1.3.1 Time to plant start-up
1.4 Establishing that the levelised cost of generation is acceptable
1.4.1 Capital costs
1.4.2 Operation and maintenance costs
1.4.3 Fuel costs
1.4.4 Decommissioning costs
1.4.5 Total production costs
1.5 Establishing that the volatility of levelised cost is low
1.5.1 Fuel price sensitivity
1.6 Establishing that hidden costs are minimal
1.6.1 Financial incentives and assistance
2 Establishing that Gas Technology is environmentally benign
2.1 Establishing that material recyclability is high
2.1.1 Recyclability of input materials
2.2 Establishing low water eco-toxicity potential
2.2.1 Freshwater ecotoxicity potential
2.2.2 Marine ecotoxicity potential
2.3 Establishing low global warming potential
2.3.1 Global warming potential
2.4 Establishing low ozone layer depletion potential
2.4.1 Ozone depletion potential
2.5 Establishing low acidification potential
2.5.1 Acidification potential
2.6 Establishing low eutrophication potential
2.6.1 Eutrophication potential
2.7 Establishing low photochemical smog potential
2.7.1 Photochemical smog potential
2.8 Establishing that impacts on land use and toxicity are low
2.8.1 Land occupation
2.8.2 Terrestial ecotoxicity potential
2.8.3 Greenfield land use

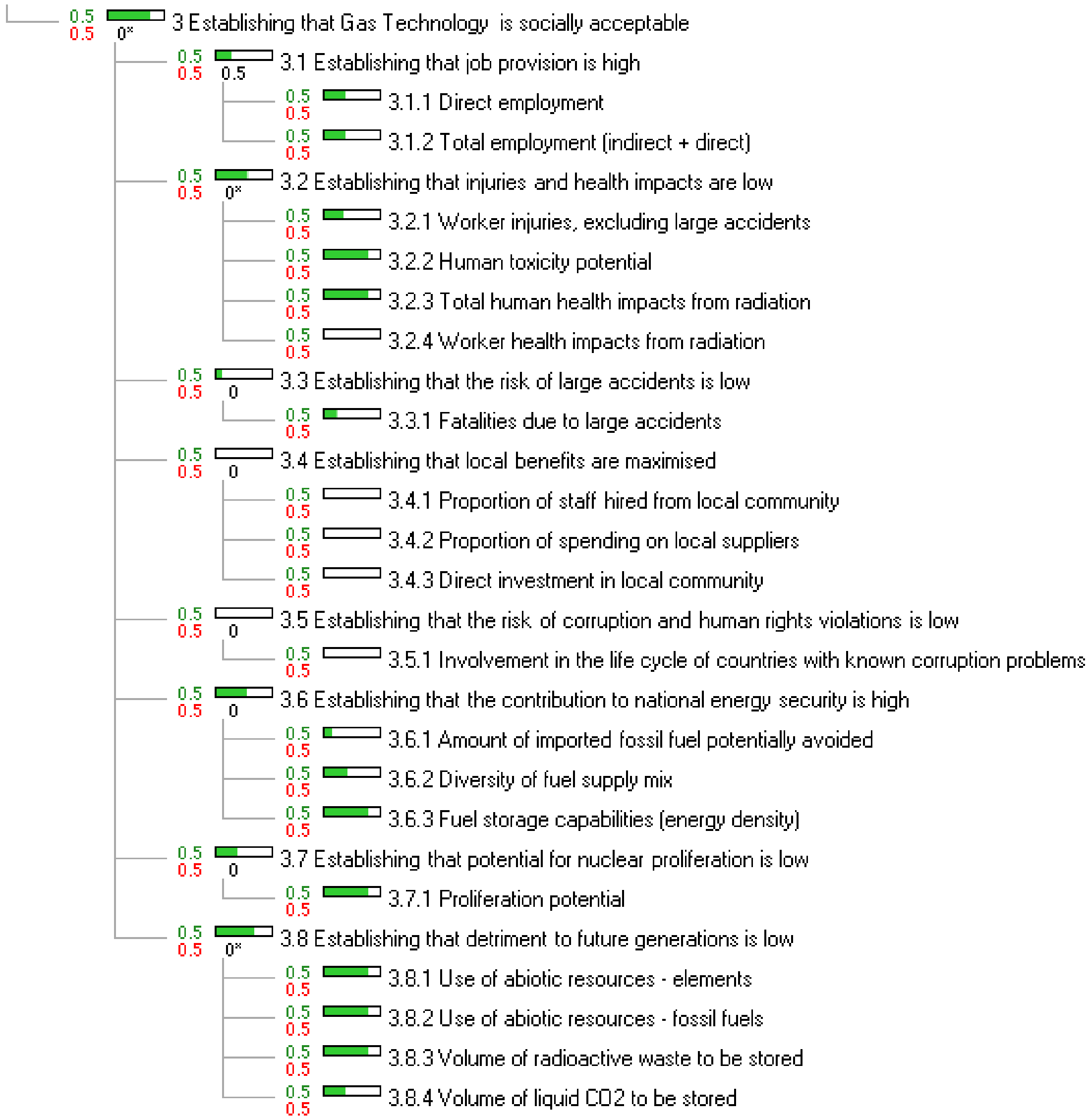


Figure 15: Data quality summary for the sustainability assessment of natural gas power

5.6 Summary

The outcomes of the life cycle sustainability assessment of natural gas power can be summarised as follows:

- At 10% discount rate, natural gas power costs £43-84/MWh (central estimate = £66/MWh). Approximately 75% of the total levelised cost is due to fuel, leaving the cost of electricity very vulnerable to natural gas markets.
- The volatility of gas prices will probably increase as reserves decline and demand increases, and particularly as the UK relies more on global trade and less on indigenous production. Global fuel reserves currently stand at around 60 years, although this could be an underestimate if unconventional reserves (such as shale gas) are exploited globally.
- CCGTs are quite dispatchable, being able to follow intermediate load. However, maintenance costs increase the more this occurs.
- Environmentally, natural gas has relatively low impacts in terms of acidification, land occupation as well as freshwater, marine and terrestrial eco-toxicity. However, as a fossil-fuelled technology, global warming potential is relatively high: for example, it is two orders of magnitude higher than that of the nuclear option. Ozone layer depletion is also high due to use of fire retardant gases in pipelines. Moreover, while LNG use reduces ozone layer depletion, it increases global warming potential by up to 35%.
- The energy security of natural gas is mixed. Diversity of fuel supply is currently quite high due to increasing availability of globally traded LNG. In contrast, energy density (and therefore fuel storage capability) is very low and indigenous production is declining.
- If LNG use continues to increase to a level where it provides 65% of natural gas supply, and if one includes full life cycle emissions of GHGs (as opposed to direct emissions, as is the case in current legislation), the upcoming Emissions Performance Standard (EPS) [28] would effectively ban the building of CCGTs - the EPS enforces a limit of 450 g CO_2/kWh which is breached beyond this level of LNG use.
- The employment provided by natural gas power is low, but consequently so is the expected number of worker injuries. Human toxicity potential is also very low, but large accident fatalities are relatively high at approximately five deaths per petawatt-hour, characterised by high frequency, medium consequence events.
- Finally, as a fossil fuel technology, depletion of fossil fuels is also high, leaving future generations with few opportunities to exploit these finite resources.

The next chapter focuses on the life cycle sustainability of coal power.

6 Coal power

This chapter presents the sustainability assessment of coal power (without carbon capture and storage) from the perspective of the UK: it is focused on coal plants reflective of those that currently provide around 28% of UK electricity (see Section 1.1); these are subcritical systems using pulverised black coal as fuel. Newer coal technologies (supercritical or ultra-supercritical) have not been considered, as new coal plants cannot be built in the UK following introduction of the Emissions Performance Standard ([28]; see below). Consequently, this assessment applies only to the current UK fleet and also provides a benchmark against which other technologies can be judged. The chapter starts in Section 6.1 with an overview of the current situation with respect to coal power in the UK. This is followed by a summary of the coal life cycle and its related sustainability issues in Section 6.2. Section 6.3 then describes the data sources and assumptions that were used to assess coal power, while Section 6.4 presents and discusses the results. Finally, Section 6.5 summarises the data quality analysis of this assessment.

6.1 Coal power in the UK: the current situation

Prior to the privatisation of the electricity sector in 1990, coal was the UK's main source of electricity, accounting for 72% of production in 1990 [26]. However, following the 'dash for gas' in the 1990s, coal's contribution fell markedly and, as of 2010, stands at 28% [5]. In conjunction with this decline, indigenous coal mining has faded rapidly in recent decades and imports now account for around 80% of steam coal supply [calculated from 16]. The UK is highly reliant on Russia for these imports (see Section 6.4.3.5).

Over the next few years, the contribution of coal power to the electricity mix will decline further as a result of the EU Large Combustion Plant Directive (LCPD) which enforces emissions constraints on power plants. Plants for which it is uneconomic to upgrade equipment to a level that would allow compliance with the LCPD (i.e. those plants that have 'opted out') must operate limited hours until 31st December 2015, at which point they must shut down [27]. In total, this applies to 7.5 GW of the 27 GW of coal plant capacity currently operating [5, 27]. Therefore, the amount of electricity generated from coal will decrease markedly in the coming years.

The recent Emissions Performance Standard will limit emissions of new generators to 450 g CO_2/kWh at the point of generation [28], which effectively bans construction of new coal plants unless they are equipped with carbon capture and storage (CCS) facilities. However, coal will still provide a sizeable share of the UK's electricity in the immediate future. Thus, as mentioned above, this sustainability assessment is intended to serve mainly as a benchmark against which other options can be judged.

6.2 Coal power life cycle and sustainability issues: an overview

The life cycle of coal power is shown in Figure 16. Coal is extracted from both opencast and underground mines before being cleaned and transported to power stations for combustion. Different grades of coal exist, being broadly classified as lignite, bituminous coal or anthracite, with purity and calorific value increasing from the former to the latter. In the UK, only bituminous coal, referred to as steam coal, is used for large-scale electricity generation. The major issues at the mining stage of the life cycle are worker health and safety and security of supply. Regarding safety, despite mechanisation decreasing injury rates, mining still has higher rates of injury and long-term health impacts than most other occupational sectors regardless of the country in which it occurs. As discussed above, the UK is now heavily reliant on other countries for its coal supplies, making security of supply a significant issue. Additionally, there may be considerable toxicity and other impacts associated with mining due to high energy requirements and emissions.

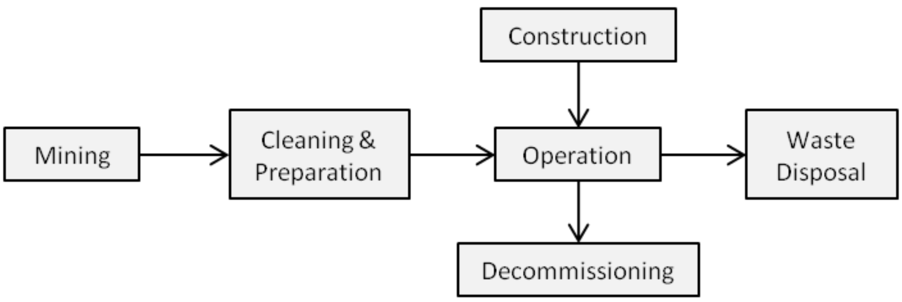


Figure 16: The life cycle of coal power

Construction and operation of a coal plant typically last 4-6 years and 40-50 years, respectively [5, 113], although plants are often upgraded and retrofitted in various stages making the duration of operation difficult to define. As with all large power plants, a high level of employment is generated during the construction period which may be beneficial to the local, as well as national, economy. Regarding the operational stage, as discussed in the previous section, subcritical pulverised coal combustion is the most widespread technology, encompassing all of the UK fleet. This involves burning coal in a boiler operating at pressures below the critical point of water (22.1 MPa [99]) typically giving a plant efficiency of 35-39%[26]. Partly as a result of this relatively low efficiency, the volume of coal required is considerable: the largest coal power station in the UK, Drax, burns around 140 train loads or 200,000 tonnes of coal per week [279, 280]. Emissions of pollutants into the atmosphere are the primary sustainability issues at this stage.

Various sustainability issues associated with different parts of the coal power life cycle are discussed further in the following sections, in conjunction with the related indicators. The indicators are, where possible, expressed per kWh electricity generated in order to enable equivalent comparisons between coal and other electricity options.

6.3 Data sources and assumptions

The key assumptions and data sources for the coal option are discussed below. Full results are given in Appendix 3. Wherever possible and available, a range of values for each option has been considered to establish the lower and upper bounds. Where appropriate, average values are used in the sustainability assessment. In other cases, 'central' estimates are used instead, representing the most likely values for present-day coal technology.

6.3.1 Techno-economic data and assumptions

The indicators used for the techno-economic assessment are shown in Table 2. The data sources used are discussed below.

[26] More modern technology is supercritical or ultra-supercritical. These involve higher pressures (and temperatures), allowing water to remain as liquid thereby avoiding the latent heat requirement caused by the state transition as water boils. Supercritical plants have efficiencies exceeding 40%, while ultra-supercritical plants approach 50% [99].

6.3.1.1 Operability

Capacity factor

The value used in the assessment is the average of UK coal plants from 2005-2009 [16]. The upper and lower bounds are the extremes from that same time period.

Availability factor

Availability factors of coal plants are not normally published in the UK. Therefore, the central figure used here is the 2005-2009 average of the 917 coal plants reporting to the North American Electric Reliability Corporation [281]: this provides a large dataset, the majority of which are subcritical units similar to those operating in the UK. The upper estimate is the 2007-2009 average for coal and biomass plants owned by Scottish and Southern Energy [261], as these are the only UK data available.

Technical and economic dispatchability

The data for the technical dispatchability of coal power, presented in Table 21 have been obtained by observing operator-specified information [95] over a period of several months. It should be noted that these figures may reflect the way in which operators choose to run their plants rather than the plants' technical abilities.

The data for economic dispatchability, estimated as a ratio of capital and total levelised costs, are based on the cost estimates described further below.

Table 21: Summary of technical dispatchability data for coal power retrieved from Balancing Mechanism Reporting System [95]

Ramp-up rate (%/min.)	worst	0.65
	average	2.25
	best	4.13
Ramp-down rate (%/min.)	worst	1.67
	average	4.28
	best	6.2
Minimum down-time (mins)	worst	360
	average	303.53
	best	240
Minimum up-time (mins)	worst	360
	average	254.12
	best	240

Lifetime of fuel reserves

The central estimate for the lifetime of fuel reserves reflects economically recoverable resources in 2010, as specified by the World Coal Institute [101] and BP [262]. It should be noted that this estimate appears to be changing rapidly, having declined from 190 years in 2003 to 119 in 2010 [282]. The lower estimate assumes that economically recoverable reserves stay the same, but demand increases at a rate of 1.6% per year, as suggested by the EIA's International Energy Outlook 2010 reference case [263], resulting in faster use of reserves. The upper estimate reflects the total recoverable resource and current production rates [283].

6.3.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

As discussed in Section 3.2.1.2, flexibility reflects the ability of each technology to provide trigeneration, net negative CO_2 emissions and high temperature (800°C) H_2 production. Ten points are accrued for each of the three criteria, with the sum being squared and divided by operational lifetime. The data for coal power are shown in Table 22.

Table 22: Data on the technological lock-in resistance of coal power

Tri-generation	yes
Net negative CO_2 emissions	no
Thermochemical H_2 production	yes
Lock-in index score (0-30)	20
Lifetime (yrs)	45
Total score (f^2/l)	**8.89**

6.3.1.3 Immediacy

Time to plant start-up

The central estimate is the average construction time of coal power stations included in the 2005 IEA Projected Costs of Generating Electricity report [113] as this provides a relatively comprehensive dataset. The lower estimate is based on the expected construction time of a recently proposed coal plant replacing the current unit at Kingsnorth, Kent [284], as this is the most recent of UK-specific estimate and reflects the lowest construction period in the dataset. The high estimate is the longest construction schedule given in the aforementioned IEA report. As this indicator measures time taken to start up the plant from the start of construction, the figures do not include planning and preliminary studies.

6.3.1.4 Levelised cost of generation

Capital, operational, fuel and total levelised costs

As for the nuclear and gas options, cost estimates are based on those by Mott MacDonald [201] at 10% discount rate. They therefore inherit most of the assumptions made there, such as plant lifespan and average capacity factor. However, these assumptions are broadly in line with those used in the rest of the assessment in this study. Any subsidies are excluded from these costs, including the carbon price applied by Mott MacDonald. The cost data are summarised in Appendix 3. The values used in this study have been verified against earlier UK cost estimates [118, 202] as well as data for other OECD countries published by IEA [99, 113] and MIT [119], but these data are not included due to obsolescence and inappropriate country-specificity.

6.3.1.5 Cost variability

Fuel price sensitivity

This indicator has been estimated using the fuel cost data and total levelised generation costs discussed in the previous section.

6.3.1.6 Financial incentives

Financial incentives and assistance

This indicator includes revenues that are available from the Renewables Obligation, the FiT and an estimate of the carbon tax avoided by ‘zero-carbon’ (at the point of generation) technologies. Coal power in the UK does not receive any of these incentives, giving a value of zero as shown in Table 23.

Table 23: Financial incentives for coal power

Number of ROCs received per MWh	0
Value per ROC 2011/12 (£)	n/a[a]
Total ROC incentive (£/MWh)	*n/a*
Value of FiT for <4 kWp in 2011/12	
new build £/MWh)	n/a
retrofit (£/MWh)	n/a
Total average FiT incentive (£/MWh)	*n/a*
Avoided emissions relative to CCGT (t CO_2/MWh)	0
Total avoided carbon price[b] (£/MWh)	*0*
TOTAL (£/MWh)	**0**

[a]n/a: not applicable
[b]Average carbon price from April 2010 to March 2011: £12.69/t CO2 [203]

6.3.2 Environmental data and assumptions

The indicators used for the environmental assessment are shown in Table 2. The key assumptions and data sources are summarised below.

6.3.2.1 Material recyclability

Recyclability of input materials

Material recyclability is the percentage of materials used for construction of a power plant that can potentially be recycled. For most construction materials, the potential recyclability is 100%. The exceptions to this are rock wool, which is assumed to be 97% recyclable [265], and concrete, which is calculated to be 79.4% recyclable [based on 204][27]. Recyclability is calculated for each technology using the amounts of construction materials given in Ecoinvent [204], as illustrated in Table 24. A plant capacity of 460 MW (based on a mix of 90% at 500 MW, 10% at 100 MW) is described in the Ecoinvent database, which is in good agreement with current coal plants in the UK: although the average capacity of coal power stations is around 1700 MW [5], such stations combine several ~500 MW units in modular fashion (for example, individual units at Ratcliffe, Aberthaw B and Cottam all lie within a range of 470-520 MW [95]). A few smaller units are also currently operating, such as the 300 MW units at Cockenzie and Kilroot [95].

[27] Concrete is typically crushed into aggregate, which may then be used to manufacture new concrete by adding new cement. In the Ecoinvent v2.2 database [204] concrete contains 1890 kg of aggregate per 2380 kg concrete (= 79.4%).

The value in Table 24 (84.3%) has therefore been selected as the central estimate for the recyclability of coal power. The lower bound (77.7%) corresponds to the amount of material that would be recycled at current UK demolition rates (see Section 4.3.2.2, Table 9).

Table 24: Major materials used for plant construction and their end-of-life recyclability for a 460 MW (average) hard coal power plant [204]

Material	Amount (t)	Recyclability (%)
Reinforcing steel	40,300	100
Chromium steel 18/8	471	100
Low-alloyed steel	4,030	100
High-density polyethylene	401	100
Copper	710	100
Aluminium	332	100
Rock wool	571	97
Concrete	148,988	79.4
Total materials	*195,803*	
Total recyclability of the plant		**84.3% (165,112 t)**

6.3.2.2 Other environmental issues

Environmental (LCA) impacts

The data for coal power have been adapted from the European hard coal subcritical power plant model in the Ecoinvent v2.2 database [204]. As discussed above, this is a hypothetical plant of 460 MW capacity based on a mix of 500 MW and 100 MW plants in a 90:10 ratio. Its efficiency is 36%. The model assumes that the plants are fitted with flue gas desulphurisation and selective catalytic reduction technologies in such a way that 90% of SO_x is captured from flue gas along with 79% of NO_x. The model was adapted to match UK conditions as follows:

- the current UK electricity mix is used for all relevant life cycle stages carried out it the UK;
- the fuel supply mix was altered to approximate current UK steam coal supply using the following supply mix: Russia, 44.3%; Western Europe, 23.9%; Latin America, 15.6%; South Africa, 8.9%; North America, 5.8%; Australia 1.5%. Note that this is an approximation due to the lack of country-specific coal mining datasets in Ecoinvent for some UK suppliers (notably the UK itself, Columbia and Indonesia; see Table 26 for the 2009 supply mix).

Following modelling of the coal life cycle as described above, sensitivity analyses were carried out to estimate the lower and upper bounds for the environmental impacts. As part of these analyses, the effect of end-of-life recycling of all major components was explored using current

UK demolition recycling rates, as described in Table 9 (see Section 4.3.2.2). This contrasts with the assumption used in the central estimate in which end-of-life recycling is not considered.

Additional sensitivity analyses have considered datasets based on operating coal plants in Germany, NORDEL (the former association of transmission system operators in Denmark, Finland, Iceland, Norway and Sweden) and eight regions of the USA [285] using existing models in the Ecoinvent database. This approach has been adopted because detailed specifications for UK coal plants are not publically available; consideration of the above Ecoinvent models allows a broad range of parameters to be considered in order to illustrate a wide range of possible results for generic present-day coal power. Parameter variations captured in the above datasets include:

- plant efficiency varied from 26 to 42%;
- SOx captured by flue gas desulphurisation varied from 24 to 90%; and
- NOx removed by selective catalytic reduction varied from 0 to 79%.

Greenfield land use

This assessment of coal power is, unlike the assessments of other technologies in this work, focused on plants currently operating in the UK rather than potential new build. This indicator cannot be assessed for extant plants due to lack of accessible information on the state of their land before construction. Therefore, this indicator is based on visual inspection, via Google Maps [215], of the land plots of the four sites proposed by large utility companies as of May 2010 (Hatfield [286], Hunterston [287], Longannet [288] and Kingsnorth [284]). Of these, all sites are brownfield apart from Hunterston, for which inspection was inconclusive: the land is partly developed and the ecological value of the remainder is unclear. Hunterston is therefore conservatively assumed to be greenfield.

6.3.3 Social data and assumptions

The indicators used for the social assessment are shown in Table 2. The data sources used are discussed below.

6.3.3.1 Provision of employment

Direct and total (including indirect) employment

To enable comparison with nuclear, natural gas and other technologies, wherever applicable the same data sources have been used for coal. Thus, employment related to the extraction of ores and aggregates (for manufacture of concrete, steel and other metals) has been calculated based on material requirements specified in Ecoinvent [204] and employment data from BHP Billiton [216] and the Mineral Products Association [217]. The processing of raw materials into metals is based on labour data from Corus [218].

Construction figures have been derived from the job requirements and schedule of the proposed 1600 MW Kingsnorth coal plant [284] which provides the only available UK-specific data for the construction stage. The operational stage is based on the jobs required to operate, maintain and support three coal power stations owned by RWE npower plc. (Tilbury, Aberthaw and Didcot A) together with their respective capacities (1131, 1500 and 2000 MW, respectively) [266]. These plants have been chosen as they provide the most comprehensive dataset of operating UK plants. As is the case for all technologies assessed in this research, maintenance employment only includes inspection and installation of replacement parts; employment owing to the manufacture of parts is excluded. Due to a lack of available estimates in the literature, employment during decommissioning is assumed to be 20% of construction employment. This is based on the approximate ratio of decommissioning cost to construction cost (see Section 4.3.3.1), and the same assumption has been maintained across all technologies assessed in this work for consistency. However, coal power plants are likely to have lower decommissioning costs than, for example, nuclear plants [99], so this may be an overestimate.

Employment due to coal mining is based on data derived from UK production statistics covering the years 2006-2010 by The Coal Authority [289]. The results were then averaged for that time period. No data were available beyond 2010. Employment and output differ between opencast and underground mining; the average figure adopted reflects a 59:41 split, respectively, corresponding to UK output in 2010. Figures include contractors. Given the fact that most steam coal is imported to the UK, indigenous employment rates were verified against those of South Africa using average data for 2008 and 2009 [290, 291]. The figures were found to be in good agreement, so UK figures were retained as the central estimate. Note that although South Africa only supplies about 10% of UK steam coal imports [16], data are not available for the main supplier, Russia.

Note that the aforementioned stages together form the total employment estimate. Direct employment is estimated by considering only the construction, operation and decommissioning stages.

6.3.3.2 Human health impacts

Worker injuries

The worker injury results are directly linked to the employment results in that the number of person-years of employment for each life cycle stage is used to calculate the number of expected injuries using Health and Safety Executive data [151] appropriate for the respective type of labour, as shown in Table 25. The exception to this is the coal mining stage, for which Australian data are used [220] due to the availability of coal-specific figures that are not available for the UK or any other coal-producing countries.

Table 25: Injury rates used to calculate worker injuries in the coal life cycle [151, 220]

Life cycle stage	HSE sector-specific injury rate used	Number of injuries per 100,000 workers
Mining of coal	Coal mining	3,160
Manufacture of plant components		
Extraction of ores/aggregates	Other mining	859.6
Processing	Manufacturing (total)	811.8
Manufacture of components	Manufacturing (total)	811.8
Construction	Construction (total)	777.2
Operation	Electricity, gas, steam and hot water supply (total)	553.8
Decommissioning	Construction (total)	777.2

Human toxicity potential & Human health impacts from radiation

These two impacts are estimated as part of life cycle assessment (see Section 6.3.2.2).

6.3.3.3 Large accident risk

Fatalities due to large accidents

As for the other electricity options considered here, large accident fatalities are based on data from the Paul Scherrer Institut [221] drawing on previous work using their historical Energy-Related Severe Accident Database (ENSAD) [222, 223]. ENSAD defines large accidents as those causing at least five fatalities. These results represent present-day Swiss conditions, but are likely to be equally appropriate for the UK: the location of the power plant is not particularly relevant in this case, as over 95% of accidents in the coal energy chain occur at the mining stage [222].

6.3.3.4 Local community impacts & Human rights and corruption

These impacts have not been considered, as they are company-specific and therefore cannot be assessed at the generic technology level.

6.3.3.5 Energy security

Avoidance of fossil fuel imports & Fuel supply diversity

The amount of imported fossil fuel potentially avoided is calculated from the average efficiency of the current UK fossil fuel fleet [calculated from 16] on the basis that a unit of electricity generated by non-fossil capacity displaces a unit generated by fossil capacity. This is described further in Section 3.2.3.6 as is the methodology of the diversity of fuel supply indicator, which has been calculated using 2009 UK data [16], as shown in Table 26. Results for earlier years have also been calculated using data from the same source [16]. These are discussed further in the results section (6.4.3.5).

Table 26: UK steam coal supply in 2009 [16] and the resulting fuel supply diversity index

	Supply (tonnes)	**Percentage of supply (%)**
Net imports	32,893,821	82.90 (*a*)
European Union	*1,136,411*	*3.45*
Australia	*444,493*	*1.35*
China	*601,653*	*1.83*
Columbia	*5,249,787*	*15.96*
Indonesia	*720,840*	*2.19*
Republic of South Africa	*3,043,122*	*9.25*
Russia	*18,471,979*	*56.16*
USA	*3,121,861*	*9.49*
Other	*103,670*	*0.32*
Simpson Diversity Index of net import mix	**0.646** (*b*)	
UK steam coal production	6,784,553	17.10 (*c*)
Total fuel supply diversity index (= *c* + *ab*)	**70.64**	

Fuel storage capabilities

Fuel storage capabilities are based on five year average net calorific value data for fuel imported to the UK [16].

6.3.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

This indicator is not applicable to the coal life cycle (for further description see Section 3.2.3.7). Therefore coal power is assigned a score of zero.

6.3.3.7 Intergenerational equity

Abiotic resources (elements and fossil fuels)

These indicators have been estimated as part of life cycle assessment (see Section 6.3.2.2).

Volume of radioactive waste and liquid CO_2 for storage

This indicator is not applicable to the coal power life cycle unless carbon capture and storage (CCS) is being considered (for further description of the indicator see Section 3.2.3.8). Given that this assessment addresses current coal capacity, and that none of that capacity is fitted with CCS equipment, coal power is assigned a score of zero.

6.4 Results and discussion

This section presents the assessment results for coal power. The summary results are shown in Figure 17, Figure 18 and Figure 19; full results can be found in Appendix 3.

6.4.1 Techno-economic sustainability

This sub-section addresses the techno-economic sustainability assessment of coal power. The results are presented in Figure 17 and discussed below.

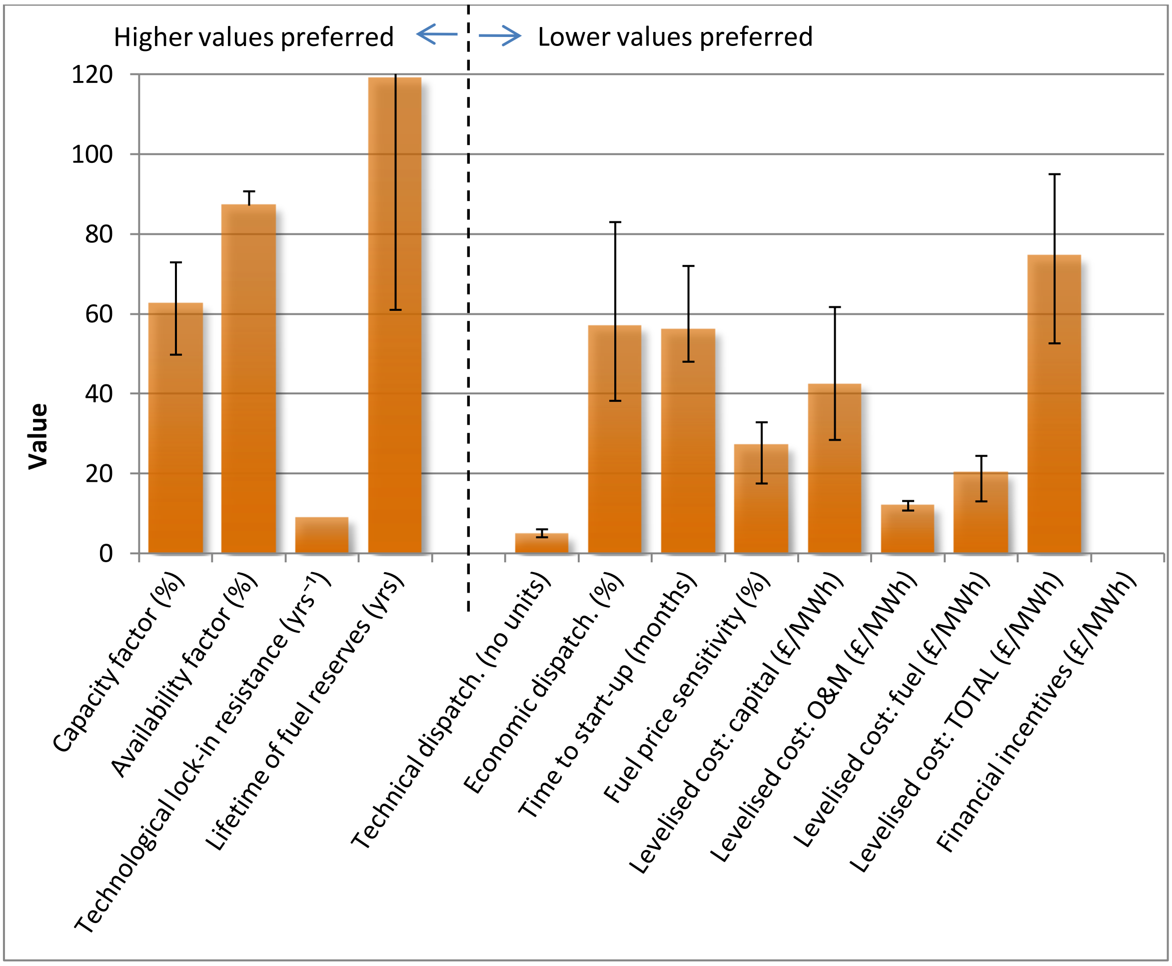


Figure 17: Techno-economic sustainability of coal power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases. The upper value of the estimate for *lifetime of fuel reserves* is 2184 years. For full results, see Appendix 3.

6.4.1.1 Operability

Capacity and availability factors

Higher availability potentially allows higher capacity factors, effectively reducing the cost (as well as social and environmental impacts) by producing more energy from the same fixed resources. As shown in Figure 17, coal power has an availability factor of around 87-91% and a capacity factor of roughly 62% (within an observed range of 50-73%). As is the case for gas power plants (CCGTs), the difference between these figures reflects the fact that the plants are typically used to partially load-follow, meaning they reduce output or shut down overnight when demand for electricity is low. This is an economic choice resulting from their relatively high marginal cost of operation (see Section 6.4.1.4). As a result, improving reliability (and thus availability) is unlikely to significantly influence capacity factors: profitability depends more upon the cost of fuel and the price of electricity sold to the grid than on the reliability of the plant. Additionally, capacity factors may be reduced at the present time as plants that have opted out of the Large Combustion Plant Directive are legally obliged to limit their hours of operation [see 292].

Technical and economic dispatchability

As mentioned above, coal plants have relatively high marginal costs due to the cost of coal (see Section 6.4.1.4): as shown in Figure 17, their capital costs comprise around half of total costs (57% in the central estimate, varying from 38.2-83%). The remainder is mainly variable costs, meaning it is often economic to follow load. In other words, economic dispatchability is relatively high, although not as high as that of a CCGT (17%, where lower values are preferable). It should be noted that, due to data limitations and in order to remain consistent with the other technologies assessed, the cost estimates used in this study are based on new build and therefore address supercritical coal plants. These plants are more advanced than an equivalent subcritical plant and therefore will have higher capital costs and lower fuel costs. Since the UK fleet is entirely composed of less efficient, subcritical plants, real-world economic dispatchability of that fleet is higher than these results suggest.

The technical ability of coal plants to load-follow is generally very good, as shown in

Table 21 (see Section 6.3.1.1): a central estimate of 4.7 (in a range of 4-6) is in fact better than the value of 7.7 attained by CCGTs since lower values are preferable. This is due to the lower complexity of a typical coal plant relative to a CCGT and the correspondingly lower maintenance costs when under a load-following regime.

Overall, coal plants are better placed to follow load than many other options. As a result, they might be expected to do this more in the future to compensate for the increasing penetration of less dispatchable options such as nuclear power and renewables.

Lifetime of global fuel reserves

At 119 years, the lifetime of global coal reserves is the longest of the main fuels (coal, gas and uranium) assuming uranium is used on a once-through cycle. Moreover, the total identified resource, at 2184 years, is much larger [283]. Coal supply, therefore, is not an obvious limiting factor in the long-term sustainability of coal power. However, currently it is not clear how economic it might be to exploit that resource, a problem that may need to be addressed sooner than expected. Coal demand is increasing quickly as developing nations, particularly China and India, require more electricity, causing a swift decline of reserve-to-production ratios in recent years: while the current lifetime is 119 years, in 2003 the estimate stood at 190 years [282]. The importance of this to future coal prices is not clear.

6.4.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

This indicator is an estimate of how well each option caters for potential changes in the way that energy is used nationally, accounting for whether it could be modified to tri-generate electricity, heating and cooling, to have negative global warming potential (e.g. integrated biomass and CCS) or to produce hydrogen at high temperatures. Coal plants are relatively resistant to technological lock-in, scoring 8.9, due primarily to their high operating temperatures which reach over 1200°C [273]. This makes them capable of trigeneration and could feasibly be used for thermochemical hydrogen production if a hydrogen economy is realised in future. However, the relatively long lifetime of coal plants (>40 years) is not preferable from the lock-in perspective, meaning coal plants are inferior to CCGTs in this respect.

6.4.1.3 Immediacy

Time to start up

A shorter construction period is preferable because it minimises uncertainty and pay-back period. Coal plants have a medium construction time, typically 48-72 months for large capacity (>1000 MW) plants. In terms of this indicator, this makes them preferable to nuclear power plants, but less desirable than CCGTs (and most renewables).

6.4.1.4 Levelised cost of generation

Capital, operational, fuel and total costs

The costs shown in Figure 17 represent the market cost of electricity generation excluding incentives provided by market mechanisms, which are discussed in Section 6.4.1.6. They are not, therefore, the net costs paid by owners. At 10% discount rate, the coal option costs 5.3-9.5 pence/kWh, with a central estimate of 7.4 pence/kWh. This is intermediate between the costs of nuclear and gas power. The cost profile of coal power is relatively uniform with capital costs accounting for around 57% of total levelised cost and fuel around 27%. This contrasts with nuclear plants, which are typically very capital intensive, and gas, which is very fuel intensive. However, as mentioned in Section 6.4.1.1, these costs are based on advanced, supercritical power plants and therefore are likely more capital intensive than traditional, subcritical plants. It is therefore probable that the cost distribution of a plant typical of the UK fleet is more uniform than these results suggest. In that case, like gas plants (see Section 5.4.1.4), potential investors would probably evaluate a coal plant at a relatively low discount rate appropriate for the up-front cost (and associated risk) of the plant.

6.4.1.5 Cost variability

Fuel price sensitivity

Fuel prices are the major component of future cost uncertainty. This is a moderate problem for coal plants, for which approximately 27% of total levelised cost is due to fuel. Fuel price sensitivity, although greater than that of a nuclear plant (6%), is therefore much more modest than in the case of gas power (74%; see Section 5.4.1.5).

6.4.1.6 Financial incentives

Financial incentives and assistance

The quantification and results of this indicator are given in Section 6.3.1.6 (see Table 23). However, coal power currently receives no incentives and, like gas, is in fact penalised by the EU Emissions Trading Scheme. The effect of this, however, is currently quite limited: for a typical coal plant emitting 900 g CO_2/kWh, the average 2010/2011 carbon price of £12.69/tCO_2 [203] equates to a penalty of 1.14 p/kWh. This adds around 15% to the total levelised cost of generation, at which point coal is still cheaper than nuclear power. The Government has proposed to introduce a carbon price floor from 2013, starting at £16/tCO_2 and rising to £30/tCO_2 by 2020 [28]; at

£30/tCO_2, the penalty for coal power becomes 2.70 p/kWh, which adds about 36% to the total generation cost, making coal appreciably more costly than nuclear power.

6.4.2 Environmental sustainability

This sub-section addresses the environmental part of the sustainability assessment of coal power. All environmental indicators, except for material recyclability and greenfield land use, have been estimated using life cycle assessment (LCA) and the CML 2001 impact assessment methodology (the November 2009 update) [59, 139]. GaBi v4.4 LCA software [244] and the Ecoinvent v2.2 database [204] have been used for these purposes. The central estimates are based on modelling undertaken in this study, but included in the possible range of values are the following models from Ecoinvent [204]:

- a hard coal power plant in Germany of 36% efficiency, with 90% SO_x capture and 79% NO_x capture;
- a hard coal power plant in the NORDEL region with an efficiency of 41.6%, a SO_x capture rate of 77% and a NO_x capture rate of 0%.
- eight hard coal power plants in the USA, each situated in a different region (ERCOT, FRCC, MRO, NPCC, RFC, SERC, SPP and WECC) with efficiencies varying from 26.1-37.5%, SO_x capture rates of 24-82% and NO_x capture rates of 22-77%.

The results are presented in Figure 18 and discussed below.

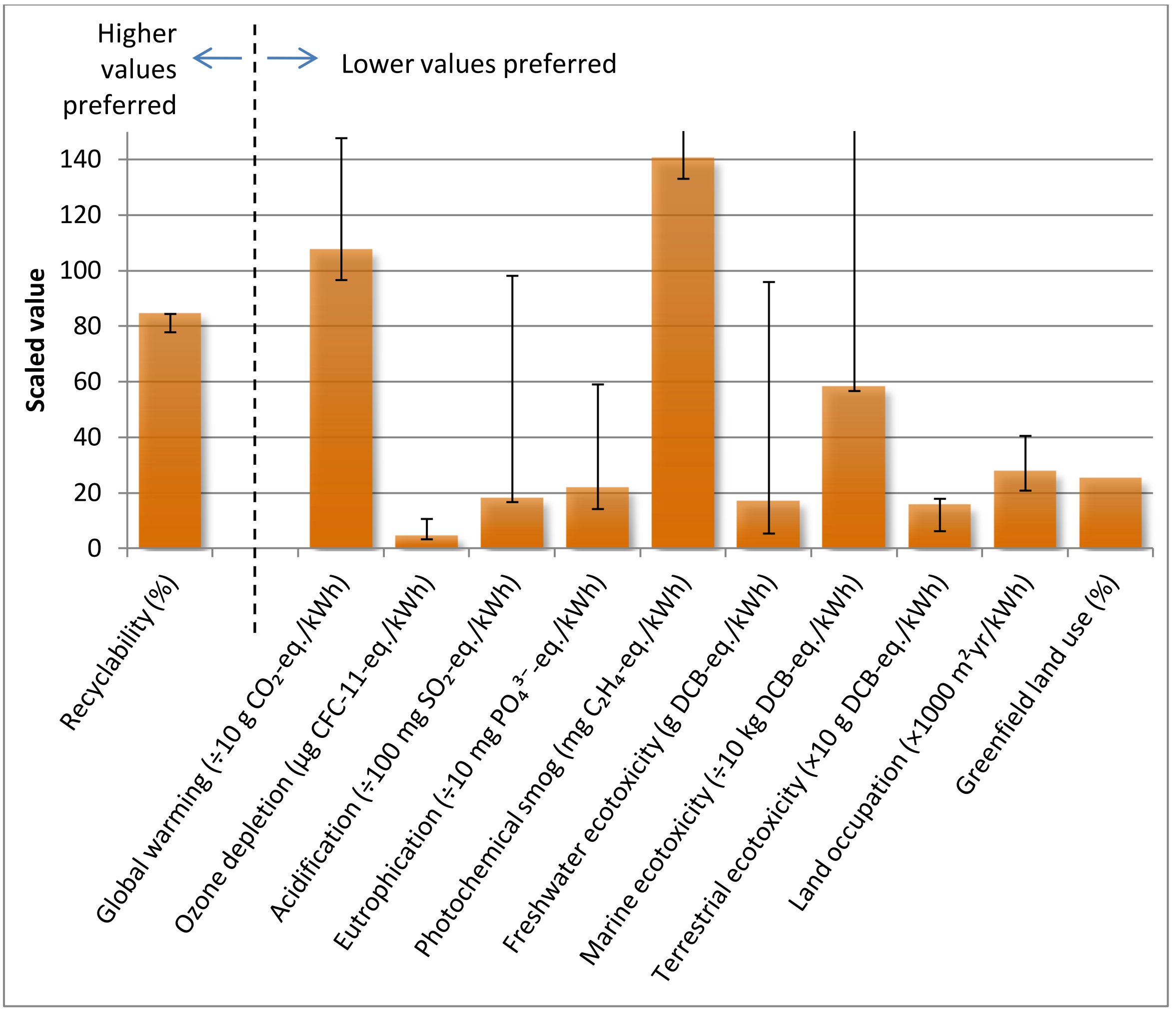


Figure 18: Environmental sustainability of coal power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled by multiplying or dividing their original values by the factors shown in brackets. Bar height represents the central estimate in all cases. The upper value of the estimate for *photochemical smog* is 457 mg C_2H_4 eq./kWh. The upper value of the estimate for *marine eco-toxicity* is 1909 kg DCB eq./kWh (190.9 on the graph's scaled *y* axis). For full results, see Appendix 3.

6.4.2.1 Material recyclability

<u>Recyclability of input materials</u>

Figure 18 (and Table 24 in Section 6.3.2.1) shows that the potential recycling rate of a coal power plant is around 84%, being limited mainly by the 149 kt of concrete required (for a 460 MW plant). At current UK demolition recycling rates (see Table 9, Section 4.3.2.2) approximately 78% of a coal power plant would be recycled. Results from the coal sensitivity analysis show that this has virtually no impact on life cycle environmental impacts, as shown in Table 27. This is because the vast majority of the impacts are caused by mining and burning coal rather than plant component manufacture, meaning recycling those components is of negligible benefit.

Table 27: Percentage reduction in impacts due to recycling of coal plant components at end-of-life, using current UK recycling rates

Impact	Reduction of impact at current UK recycling rates[a] relative to no recycling (%)
Global warming potential	0.06
Ozone depletion potential	0.54
Acidification potential	0.17
Eutrophication potential	1.34
Photochemical smog potential	0.42
Freshwater eco-toxicity potential	2.73
Marine eco-toxicity potential	0.25
Terrestrial eco-toxicity potential	-0.30[b]

[a] Aluminium 95%, other metals 99%, plastics 26%, concrete 71.5%, fibre cement facing tile 0%, paper 69%, gravel 30%, glass fibre reinforced plastic 10%, ceramic tiles 64%, insulation 18%, glass 0% (see Section 4.3.2.2).

[b] Recycling slightly increases this impact because of the processes involved. Most primary steel is produced via basic oxygen steelmaking, whereas recycling is only done in electric arc furnaces. In this case, there is a slightly greater terrestrial eco-toxicity potential associated with production in an electric arc furnace than in the basic oxygen process, resulting in an increased impact due to recycling.

6.4.2.2 Global warming potential (GWP)

As shown in Figure 18, the central estimate for the GWP of coal power is 1072 g CO_2 eq./kWh, which is considerably higher than the current average UK electricity value of 584 g CO_2 eq./kWh [204] reflecting the fact that coal is the most GHG-intensive power source in use today in the UK. This estimate is in agreement with the range of 800-1100 g CO_2 eq./kWh given by a recent UK review [293]. Its place at the higher end of the range reflects the fact that it describes traditional subcritical coal power plants rather than new ultra-supercritical designs (see Section 6.2). The lower estimate shown in Figure 18 (965 g CO_2 eq./kWh) corresponds to the GWP of coal plants in the NORDEL region (Denmark, Finland, Iceland, Norway and Sweden) which, being supercritical, are more advanced than the UK's subcritical units but less advanced than ultra-supercritical designs. This gives the NORDEL model an average efficiency significantly higher than the central model (41.6% c.f. 36%). However despite this efficiency advantage, GWP is still approximately 155 times that of nuclear power. As a result, the Emissions Performance Standard (EPS) [28] clearly bans the construction of any coal plants in the UK – whether subcritical, supercritical or ultra-supercritical – by enforcing a limit of 450 g CO_2/kWh. Therefore, any new coal plants will have to be built with carbon capture and storage (CCS): this is considered in Chapter 9.

6.4.2.3 Ozone layer depletion potential (ODP)

Coal power has an ODP of 4.25 μg CFC-11 eq./kWh in the central case, with a potential range of 3.2-10.5, the range being determined mainly by the efficiency of the plant and its resultant fuel use. This is an order of magnitude higher than the value for nuclear power (see Section 4.4.2.3), but less than half that of gas power (Section 5.4.2.3). The majority (87%) of the ODP of coal power results from use (and leakage) of Halon 1301 and 1211, both of which are fire and explosion suppressants. Around half of the Halon emissions are attributable to the heavy fuel oil production chain that supplies the oceanic transportation required by international coal trade. Coal production itself, as well as non-oceanic transportation, accounts for the remainder.

6.4.2.4 Acidification potential (AP)

The life cycle AP of coal power is estimated at 1.78 g SO_2 eq./kWh (within a range of 1.66-9.80). This is around 12 times the impact of natural gas power (Section 5.4.2.4). Over 60% of this impact results from emission of SO_2 and NO_x during coal combustion, despite the central model assuming 90% and 79% capture of those pollutants by pollution control technologies (flue gas desulphurisation and selective catalytic reduction), respectively. The effect of less stringent pollution control is illustrated by the sensitivity analysis: results for the North American coal plants that report to the ReliabilityFirst Corporation (which covers 13 eastern states) show an AP of 9.80 g SO_2 eq./kWh due to an average SO_2 capture rate of just 24%.

6.4.2.5 Eutrophication potential (EP)

Coal power has an EP of 0.215 g PO_4^{3-} eq./kWh in the central case, with a possible range of 0.141-0.589. The biggest single contributor (68%) is NO_x emitted to air throughout the coal mining, transportation and combustion stages. This result is more than three times that of gas power (see Section 5.4.2.5). Because the impact is caused mainly by combustion of coal, it correlates with plant efficiency: the worst result obtained (0.589 g PO_4^{3-} eq./kWh) corresponds to plants in the Midwest Reliability Organisation region with an average efficiency of just 26.1%.

6.4.2.6 Photochemical oxidant creation potential (POCP)

The POCP of the coal life cycle is estimated to be 0.140 g C_2H_4 eq./kWh. This is a factor of 28 higher than the impact of nuclear power (see Section 4.4.2.6). Around half of this impact (52%) is due to emission of methane, VOCs, SO_2 and NO_x during the mining and transportation of coal.

The remainder of the impact mostly results from emission of VOCs, SO_2 and NO_x during the combustion of coal to generate electricity. The potential range of results for POCP is 0.133-0.457 g C_2H_4 eq./kWh, with the upper estimate reflecting the low average SO_2 capture rate (24%) of plants in the ReliabilityFirst Corporation area.

6.4.2.7 Water eco-toxicity

Freshwater eco-toxicity potential(FAETP)

Coal power has a FAETP of 16.8 g DCB eq./kWh. This is slightly less than the 21.1 g attributable to the nuclear life cycle (see Section 4.4.2.7). However, the range of possible values for coal power spans 5.3-95.8 g DCB eq./kWh and corresponds closely to the efficiency of the plant in question: the lowest value is attributable to the 41.6% efficient NORDEL plant model, while the highest impact is from the 26.1% efficient MRO model. Almost all (98%) of the impact is due to emissions of metals such as beryllium, vanadium and nickel to fresh water throughout the life cycle.

Marine eco-toxicity potential (MAETP)

The coal life cycle has a MAETP of 566-1909 kg DCB eq./kWh with a central estimate of 578 kg DCB eq./kWh. This is high, comparing to around 40 g for the nuclear life cycle and 7 for natural gas (see Sections 4.4.2.7 and 5.4.2.7). The majority (92%) of this impact is due to the emission of hydrogen fluoride to air during the combustion of coal in the power plant, and therefore depends on the composition of the coal being burned and combustion efficiency of the plant.

6.4.2.8 Land use and quality

Terrestrial eco-toxicity potential (TETP)

As shown in Figure 18, the TETP of the coal life cycle is 1.53 g DCB eq./kWh (in a range spanning 0.61-1.78). Emission of mercury when coal is burned in the power plant accounts for 76% of this impact.

Land occupation

Generating electricity from coal uses approximately 0.0273 m^2yr/kWh along the life cycle, which is a factor of 40-50 times the land occupation of nuclear or gas power. Less than 0.25% of this is caused by the power plant itself, while over 96% of the total is due to the large area required for mining and associated facilities. The minimum and maximum values for this indicator (0.0207 and 0.0404 m^2yr/kWh, respectively) are therefore dictated by the volume of coal burned, which in turn depends on plant efficiency and the calorific value of the coal used.

Greenfield land use

The greenfield land use indicator is intended to describe the percentage of new power plants likely to be built on greenfield land and as such only the operational stage is considered. Of the four sites proposed by large UK utility companies as of May 2010 (see Section 6.3.2.2), three are on brownfield sites and one is on an inconclusive site that is conservatively assumed to be greenfield. This gives a score of 25% (see Figure 18).

6.4.3 Social sustainability

This sub-section addresses the social part of the sustainability assessment of coal power. The results are presented in Figure 19 and discussed below.

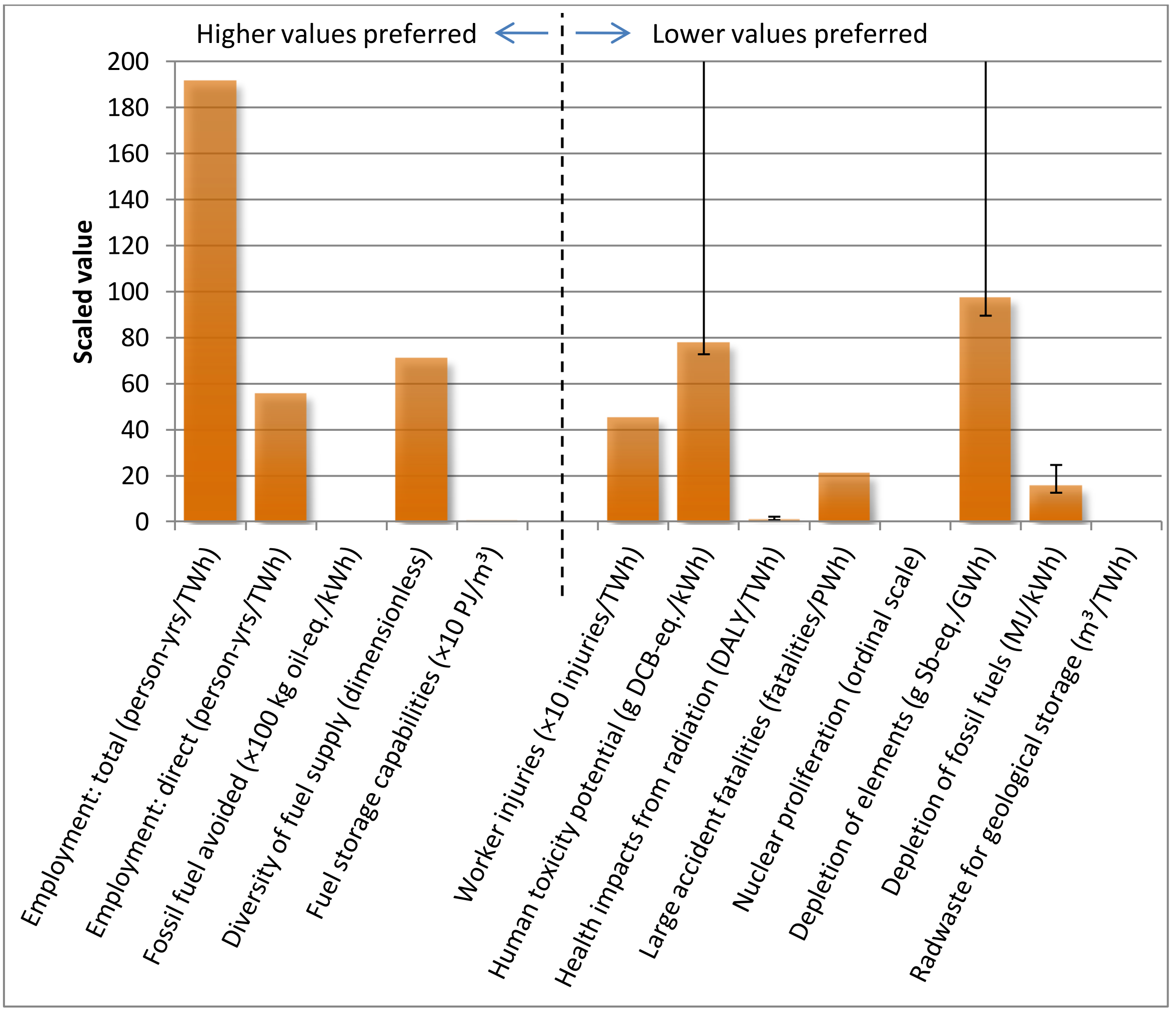


Figure 19: Social sustainability of coal power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled by multiplying or dividing their original values by the factors shown in brackets. Bar height represents the central estimate in all cases. The upper value of the estimate for *human toxicity potential* is 458 g DCB eq./kWh. The upper value of the estimate for *depletion of elements* is 350 g Sb eq./GWh. For full results, see Appendix 3.

6.4.3.1 Provision of employment

<u>Total employment</u>

Total employment estimates in Figure 19 comprise direct and indirect employment. The former is related to the power plant erection, operation, maintenance and decommissioning while the latter refers to jobs in fuel extraction and production, waste management and other services to the plant over its lifetime. The results show that coal power provides 191 person-years/TWh of employment, but only 29% of this is direct (i.e. specifically related to the power plant site). During construction, employment is high; for example, a 1600 MW plant provides an average of around 1500 jobs throughout the construction period [calculated from 284]. The same plant would employ approximately 400 people throughout its operational life. However, 68% of total employment is in coal mining and is therefore spread across the various countries from which the UK imports coal.

Direct employment

When indirect employment is excluded from the total, coal power provides 55.6 person-years/TWh of direct employment, 74% of which is due to the operational stage discussed above.

6.4.3.2 Human health impacts

Worker injuries

The coal life cycle is estimated to cause 4.5 injuries/TWh (Figure 19) which is around eight times higher than either the nuclear or gas life cycle (Sections 4.4.3.2 and 5.4.3.2). This reflects the labour intensive nature of coal mining and its related dangers: as shown in Table 25 (see Section 6.3.3.2) injury rates are relatively high in the mining sector, which provides 68% of total employment.

Human toxicity potential (HTP), excluding radiation

Coal power has a HTP of 77.7 g DCB eq./kWh in the central estimate. This is intermediate between the impacts of natural gas and nuclear power. The operational stage is responsible for 69% of this impact as a result of aerial emissions of toxic substances such as hydrogen fluoride, arsenic and benzene during coal combustion. The American power plants included in the modelling have significantly higher HTP than the European ones: the worst, MRO, emits 352 g DCB eq./kWh. This is a result of a greater concentration of heavy metals in North American coal and, particularly in the MRO case, low power plant efficiency (26.1%).

Total human health impacts from radiation

The health impact of radiation from the coal life cycle is 0.71 disability-adjusted life years (DALYs) per TWh (Figure 19). This is nearly three times as high as the gas power life cycle, but much lower than the 20.3 DALYs attributable to nuclear power. Emission to air of carbon-14, thorium-230 and radon-222 during coal mining causes 95% of this impact. As is the case for HTP, American plants have higher radiation-related heath impacts than European plants, giving impacts as high as 2.21 DALYs/TWh (in the case of MRO). Again, this is due primarily to coal composition, as well as plant efficiency in the worst cases. The worst-case impact is still, however, nine times lower than that of nuclear power.

6.4.3.3 Large accident risk

Fatalities due to large accidents

The Paul Scherrer Institut estimate that a present-day coal plant and its associated energy chain cause 20.7 fatalities/PWh [221]. This is around four times higher than gas power and 17,000 times higher than the estimated rate for Generation III nuclear power. This is caused by the high frequency and high impact of coal mining accidents [221].

6.4.3.4 Local community impacts and human rights & corruption

As mentioned in Section 6.3.3.4, these impacts have not been considered because they are company-specific and therefore not applicable for technology assessment. For further discussion, see Section 3.2.3.

6.4.3.5 Energy security

Avoidance of fossil fuel imports

As a fossil fuel option, coal power does not avoid fossil fuel imports. Indeed, given the low level of indigenous production (discussed below) and the low efficiency of coal power plants (discussed in Section 6.3.2.2), coal arguably requires more fuel importation per unit of electricity generated than any other large-scale option.

Diversity of fuel supply mix

This indicator reflects the resilience of national electricity production to fuel supply disruptions, whether they are economic, technical or political. Coal production in the UK has declined markedly over the last few decades. Consequently, in 2009 the UK only produced 17.1% of its steam coal (used for electricity generation) indigenously while the remainder was imported from various countries, predominantly Russia (56% of imports) (see Section 6.3.3.5). The Simpson Index of Diversity for the steam coal import mix is 0.65 (see Table 26 in Section 6.3.3.5 and Appendix 2 for the methodology), giving an overall diversity of fuel supply (DFS) mix of 0.71 (= $0.171 + (0.829 \times 0.646)$). To put this in context, data from Ukraine were also analysed. In

2005/06, Ukraine's dispute with Russia over natural gas supply created significant social and economic tension across Europe as supplies were disrupted. This acts as a good illustration of the consequences of low supply diversity. Ukraine's 2005 natural gas mix comprised 36 billion m^3 from Turkmenistan, 24 billion m^3 from Russia and 20 billion m^3 of indigenous production [294]. As shown in Figure 20, the UK coal supply mix is declining in diversity to the extent that it is rapidly approaching Ukraine with respect to gas supply diversity for that year.

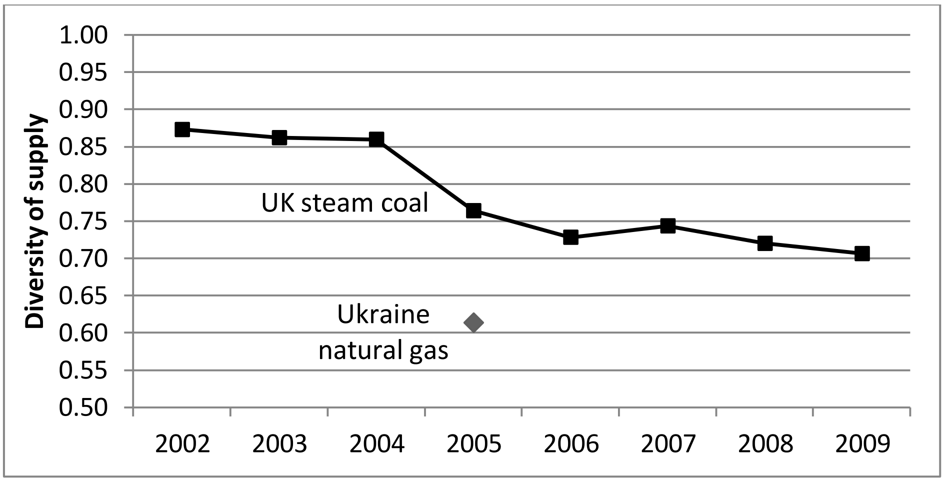


Figure 20: Historical results illustrating the diversity of UK steam coal supplies (Ukraine's diversity of gas supplies shown for comparison)

Fuel storage capabilities

This indicator shows inherent resilience: energy dense fuels are physically easier to transport and store to be used when supply is problematic. Coal has a net energy density of approximately 21 GJ/m^3 [calculated from 275]), compared to 0.035 GJ/m^3 in the case of natural gas. Despite this obvious advantage over gas, the energy density of coal is still insufficient to avoid potential supply problems due to fuel storage capabilities. This is illustrated by the fact that Drax, the largest coal power station in the UK, uses around 140 train loads or 200,000 tonnes of coal per week [279, 280]. As a result, a reliable, constant supply is an absolute requirement. In contrast, a nuclear power plant could extract the same amount of energy from 490,000 times less fuel, or roughly 400 kg (based on PWR fuel assemblies and burn-up of 50 GWd/tU; see Section 4.4.3.5); this corresponds to approximately half of one fuel assembly (based on AREVA EPR [170]).

6.4.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

This indicator is not applicable to coal power, so it has a score of zero.

6.4.3.7 Intergenerational equity

Use of abiotic resources (elements)

As indicated in Figure 19, use of abiotic elements in the coal life cycle totals 97.2 g Sb eq./GWh. Most of this impact (88%) is due to the use of chromium, copper, gold and molybdenum throughout the life cycle, with coal mining and transportation accounting for 76% of the total. Sensitivity analysis shows that the result can be as high as 350 g SB eq./GWh (in the case of the Midwest Reliability Organisation region of the USA) due to an inefficient coal sourcing chain and inefficient plants (therefore higher coal requirement per unit output).

Use of abiotic resources (fossil)

Fossil resource depletion in the coal life cycle is 15.1 MJ/kWh. Because 97% of this impact is due to coal combustion during operation and mining, the total fossil fuel depletion is almost entirely dependent on the efficiency of the plant and the energy intensity of the mines from which its fuel is derived. Variation of these factors captured within the LCA models produced a range of 12.6-24.7 MJ/kWh, with the high value corresponding again to the MRO region of the USA (average plant efficiency = 26.1%).

Volume of radioactive waste and liquid CO_2 to be stored

Coal power in its current form does not produce radioactive waste or liquid CO_2 for storage. However, this indicator is applicable to coal with carbon capture and storage. As discussed in Chapter 9, assuming a carbon capture rate of 90%, direct emissions of 790 g CO_2/kWh and an injection pressure of 110 bar (which corresponds to that of Leman, the biggest UK gas field being considered for CO_2 storage [295]), this equates to 7.48×10^{-4} m^3 CO_2/kWh. The equivalent figure for radioactive waste production from new nuclear build is 1.02×10^{-8} m^3/kWh (see Section 4.4.3.7).

As an illustration, if all electricity generated annually in the UK (~380 TWh [5]) was via coal CCS, this would produce 284 million m^3 of pressurised, liquid CO_2 per year: about 4% the volume of Loch Ness [296].

6.5 Data quality in the coal power assessment

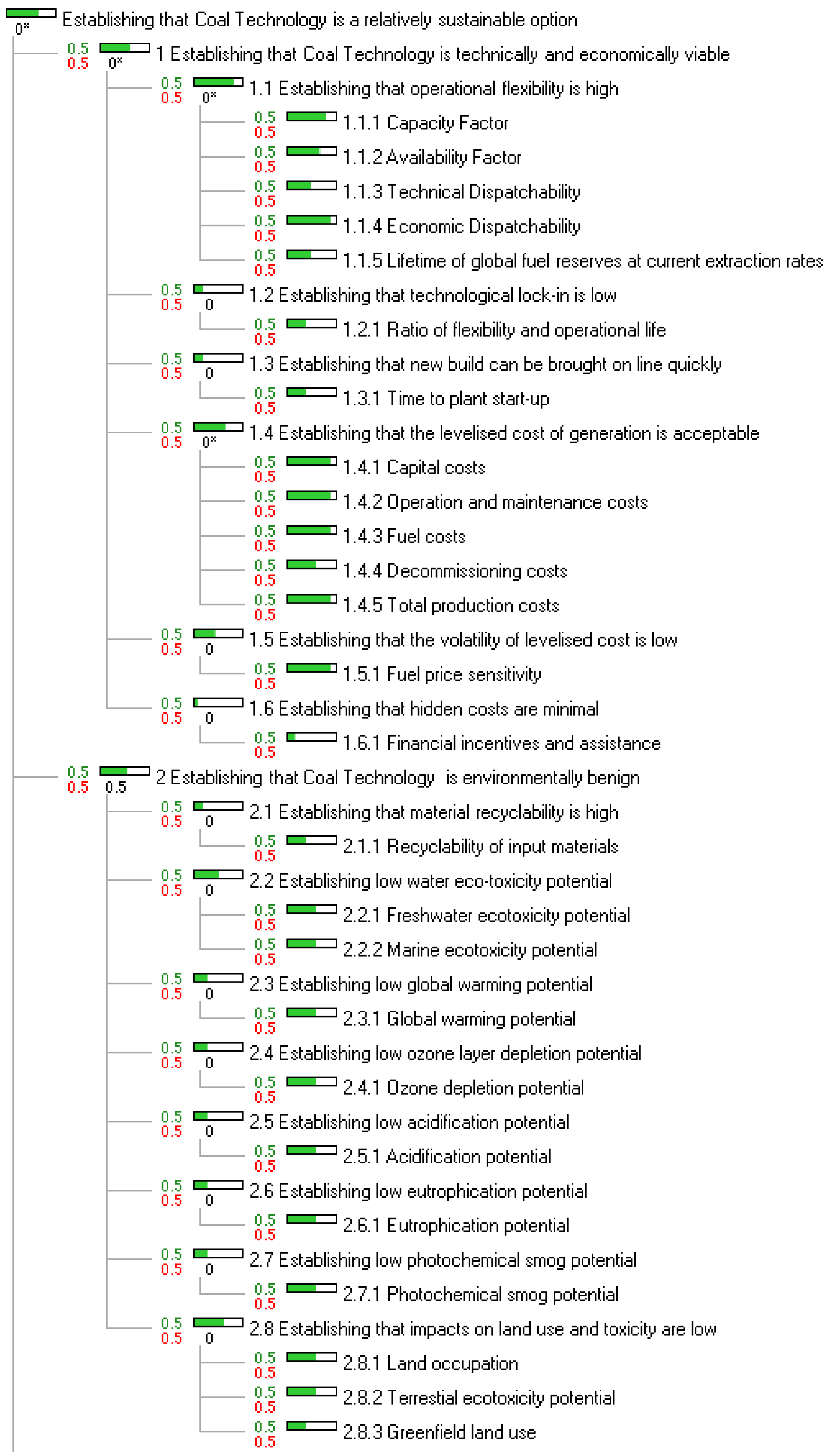
Data quality has been assessed using the same methodology as for the nuclear option and the other options assessed in this work (see Section 4.5 and Appendix 4).

Figure 21 shows a summary of the data quality analysis. The overall assessment is rated at 67% (where a rating of 100% would indicate perfect quality). This is very similar to the ratings for nuclear power (66%) and natural gas power (68%).

The weakest of the three 'pillars' is the environmental group, scoring 55.2%. The main reasons for this are lack of technological specificity and high dependency due to the LCA indicators sharing common data sources. The lack of technological specificity is due to the adoption from Ecoinvent of a coal plant dataset representing Germany, meaning plant efficiency and pollution control measures match German conditions rather than those of the UK. This is not a problem in terms of plant efficiency, which is in good agreement with the UK average, but UK-specific data on adoption of flue-gas desulphurisation and selective catalytic reduction technologies are lacking.

Overall, the data quality of the coal sustainability assessment is thought to be good considering the purposes of this study: that is, an assessment of a generic subcritical coal plant in the UK to be used as a benchmark against which other electricity options might be evaluated. Improvements could be made by focusing on lower rated areas shown in Figure 21 as shorter green bars, as follows:

- extending the assessment of financial incentives and assistance to include hidden subsidies as discussed in Section 3.2.1.6;
- improving the employment estimate by including Russian figures for the coal mining stage;
- improving the worker injury estimate by adding data for Russian coal mining; and
- increasing the accuracy of the LCA model of the power plant itself by accounting for average UK adoption of pollution control measures.


0* Establishing that Coal Technology is a relatively sustainable option
0.5 0.5 0* 1 Establishing that Coal Technology is technically and economically viable
0.5 0.5 0* 1.1 Establishing that operational flexibility is high
0.5 0.5 1.1.1 Capacity Factor
0.5 0.5 1.1.2 Availability Factor
0.5 0.5 1.1.3 Technical Dispatchability
0.5 0.5 1.1.4 Economic Dispatchability
0.5 0.5 1.1.5 Lifetime of global fuel reserves at current extraction rates
0.5 0.5 0 1.2 Establishing that technological lock-in is low
0.5 0.5 1.2.1 Ratio of flexibility and operational life
0.5 0.5 0 1.3 Establishing that new build can be brought on line quickly
0.5 0.5 1.3.1 Time to plant start-up
0.5 0.5 0* 1.4 Establishing that the levelised cost of generation is acceptable
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0.5 0.5 1.4.2 Operation and maintenance costs
0.5 0.5 1.4.3 Fuel costs
0.5 0.5 1.4.4 Decommissioning costs
0.5 0.5 1.4.5 Total production costs
0.5 0.5 0 1.5 Establishing that the volatility of levelised cost is low
0.5 0.5 1.5.1 Fuel price sensitivity
0.5 0.5 0 1.6 Establishing that hidden costs are minimal
0.5 0.5 1.6.1 Financial incentives and assistance
0.5 0.5 0.5 2 Establishing that Coal Technology is environmentally benign
0.5 0.5 0 2.1 Establishing that material recyclability is high
0.5 0.5 2.1.1 Recyclability of input materials
0.5 0.5 0 2.2 Establishing low water eco-toxicity potential
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0.5 0.5 2.4.1 Ozone depletion potential
0.5 0.5 0 2.5 Establishing low acidification potential
0.5 0.5 2.5.1 Acidification potential
0.5 0.5 0 2.6 Establishing low eutrophication potential
0.5 0.5 2.6.1 Eutrophication potential
0.5 0.5 0 2.7 Establishing low photochemical smog potential
0.5 0.5 2.7.1 Photochemical smog potential
0.5 0.5 0 2.8 Establishing that impacts on land use and toxicity are low
0.5 0.5 2.8.1 Land occupation
0.5 0.5 2.8.2 Terrestial ecotoxicity potential
0.5 0.5 2.8.3 Greenfield land use

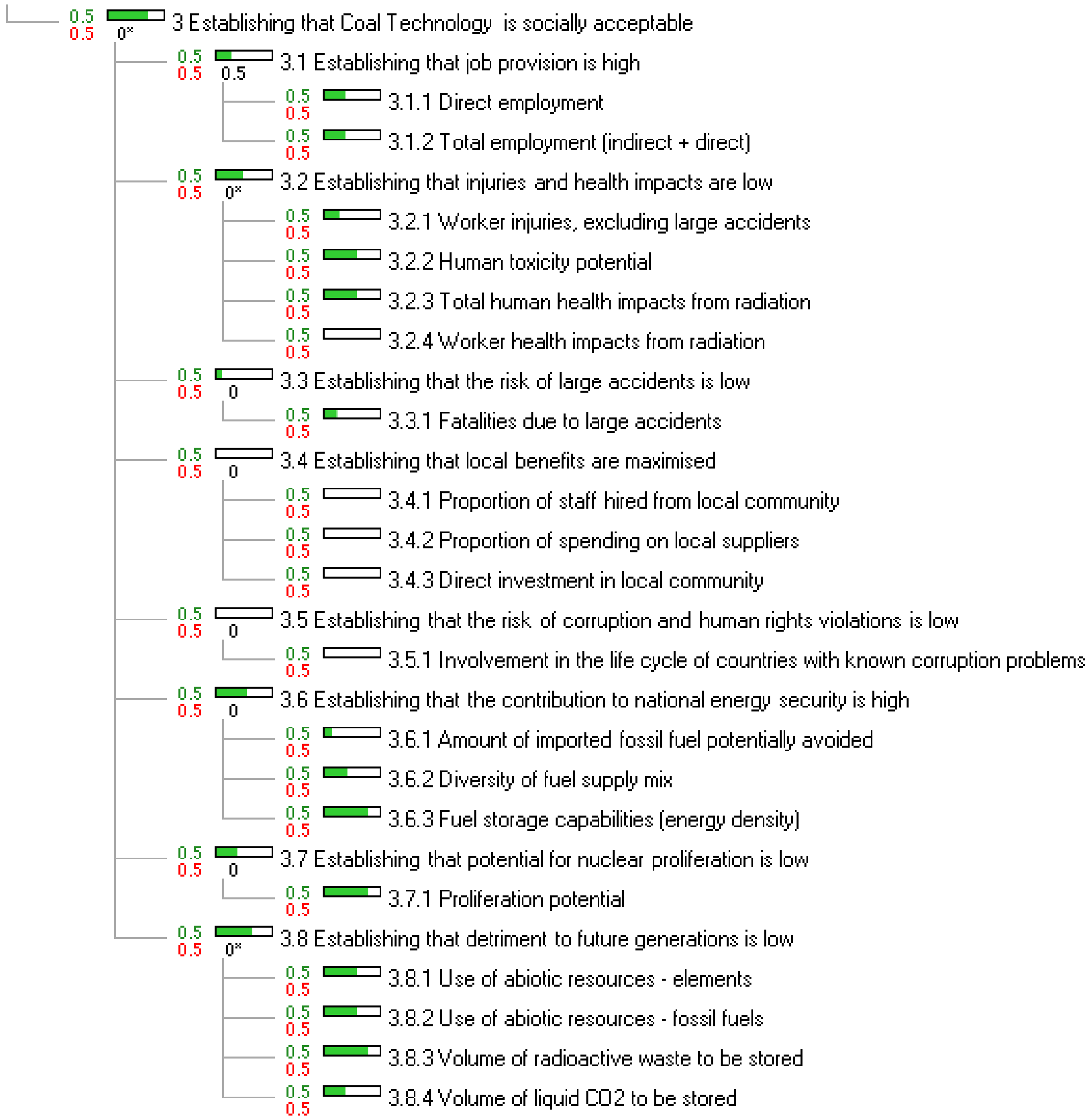

Figure 21: Data quality summary for the sustainability assessment of coal power

6.6 Summary

The outcomes of the sustainability assessment of coal power can be summarised as follows:

- Coal power is a relatively cheap source of electricity (5.3-9.5 pence/kWh; central estimate 7.4 pence/kWh). Its cost profile is relatively evenly split between capital, operation and fuel costs. As a result, it has a fuel price sensitivity of around 30%, exposing consumers to less price volatility than natural gas (c.f. 74%) but more than nuclear power (6%).
- However, despite its low cost, imminent regulations requiring all new power plants to emit less than 450 g CO_2/kWh means that new coal plants cannot be built without carbon capture and storage facilities, significantly increasing costs.
- Global fuel reserves currently stand at around 119 years, although this has declined rapidly in the last decade as demand increases in developing countries. The total coal resource, at over 2000 years, is very large but the cost of exploitation of most of this resource is not clear.
- Coal plants are quite dispatchable, being able to follow intermediate load. This will be an important characteristic if less flexible generators such as nuclear and wind power become more commonplace.
- Environmentally, coal has high global warming, acidification, eutrophication, photochemical smog, marine eco-toxicity and land occupation potentials.
- Coal power provides low levels of energy security. Diversity of fuel supply is currently quite low and declining due to decreasing indigenous production and over reliance on Russian imports. The diversity of coal supply is gradually approaching the level experienced by Ukraine during its 2005 natural gas dispute. Coal's energy density is several times that of natural gas, but at 490,000 times lower than that of nuclear fuel, it is still not high enough to tolerate significant disruptions to fuel supplies.
- Coal power provides high levels of employment, but 68% of that is in coal mining, and consequently worker injury rates are high.
- Additionally, large accident fatalities in the coal life cycle are extremely high compared to other options, with the vast majority of these occurring in mines.
- Finally, as a relatively inefficient fossil fuel technology, depletion of fossil fuels is very high, reducing the exploitable resource for future generations.

The next chapter focuses on the life cycle sustainability of electricity from offshore wind.

7 Offshore wind power

This chapter describes the sustainability assessment of offshore wind power from the perspective of current new build in the UK: it is therefore focused on wind farms comprising turbines of 2 MW and higher capacity. Offshore, rather than onshore, wind power has been assessed due to its greater potential to contribute to the national electricity mix and its current higher rate of growth. The chapter starts in Section 7.1 with an overview of the current situation with respect to offshore wind power in the UK. This is followed in Section 7.2 by a summary of the life cycle of offshore wind power and its related sustainability issues. Section 7.3 then describes the data sources and assumptions that were used in the assessment, while Section 7.4 presents and discusses the results. Finally, Section 7.5 summarises the data quality analysis of this assessment.

7.1 Offshore wind power in the UK: the current situation

The European Wind Atlas demonstrates that the UK has the highest average wind speeds in Europe, both on- and offshore [297]. Indeed, it has been claimed that the UK has around 40% of the total European wind resource [298]. However, wind power in the UK has been slow to gain prominence and, in 2010, still only accounted for 2.8% of electricity generation with a 70:30 split between onshore and offshore production, respectively [5]. However, offshore wind in particular receives significant support from government policy via the Renewables Obligation [12] (the main stimulus for large-scale renewable energy technologies in the UK). Offshore wind receives between 1.5 and 2 Renewables Obligation Certificates (ROCs) per MWh produced, which compares to one ROC/MWh for most other renewables, including onshore wind and hydroelectricity. Since the introduction of ROCs in 2002, UK offshore wind capacity has increased almost 500-fold (as of April 2012; calculated from [5] and [13]). This has made the UK the global leader with an installed capacity of 1858 MW, representing about half of the worldwide total [299]. Thanet, off the coast of Kent, and Walney, off the coast of Cumbria, are the two largest offshore wind farms in the world at the time of writing; they were completed in 2011 and 2012, respectively [300].

Growth in offshore wind will be high in the near future: The Crown Estate has been awarding sites in UK waters in three 'rounds' of development, each successively larger than the last, with all three rounds (yet to be completed) having a total potential installed capacity of 33 GW [10]. At the time of writing, a total capacity of 7.2 GW of offshore wind power is currently under construction, consented or in planning [13].

7.2 Offshore wind power life cycle and sustainability issues: an overview

The life cycle of offshore wind power is shown in Figure 22. Being a fuel-free technology, wind power has a simpler life cycle than nuclear, coal or gas power, consisting only of construction, operation and decommissioning. In Figure 22 construction has been disaggregated into its component stages of raw material extraction and processing, manufacture of components and finally erection of turbines at the wind farm site. Like other electricity technologies, the raw material stage involves the mining and processing of ores into basic materials. As for all mining and heavy industry processes, the major sustainability issues at this stage are worker safety and the environmental impacts that result from such energy-intensive activity. Leaching of toxic substances and depletion of abiotic resources are also important. Following raw material appropriation, manufacturing takes place, in which components for the turbine and its related infrastructure are produced. These include generators, turbine towers, blades and nacelle components. Similarly to the raw material sourcing stage, manufacturing of large components is energy-intensive and therefore associated with significant emissions. However, due to the large amount of materials required, considerable employment can be generated in these stages.

Figure 22: The life cycle of offshore wind power

The cost of offshore wind power, affected primarily by the capital cost of components and erection, is also a relevant issue, with investors currently relying on subsidies to make this option financially viable.

Erection and operation of a wind farm typically last 4-20 months and 20-25 years, respectively [300]. However, the construction duration is clearly dependent on the size of the installation as well as other factors such as distance from shore. The operational stage may exceed 40 years if the wind farm is ‘repowered’; that is, the turbines themselves are upgraded while retaining the associated foundations and infrastructure. The erection and operational stages of the life cycle provide labour opportunities, many of which are specialised and skilled, occurring as they do in a marine environment. There are very few environmental impacts associated with the operational stage of the wind power life cycle, which is one of the main drivers of their growth. Visual impact is often highlighted as an issue of concern for wind farms, however this is subjective and, although a polarising topic, often results in as many people in favour as those against [see, for example, 301, 302]. Another potential issue in the operational stage is dispatchability: wind power is variable in output, therefore as the capacity of wind power attached to the grid increases, the ability of grid operators to balance supply and demand is diminished.

Various sustainability issues associated with different parts of the offshore wind power life cycle are discussed further in the following sections, in conjunction with the related indicators. The indicators are, where possible, expressed per kWh electricity generated in order to enable equivalent comparisons between wind and other electricity options.

7.3 Data sources and assumptions

The key assumptions and data sources for the offshore wind option are discussed below. Full results are given in Appendix 3. Wherever possible and available, a range of values for each option has been considered to establish the lower and upper bounds. Where appropriate, average values are used in the sustainability assessment. In other cases, 'central' estimates are used instead, representing the most likely values for new offshore wind farms.

7.3.1 Techno-economic data and assumptions

The indicators used for the techno-economic assessment are shown in Table 2. The data sources used are discussed below.

7.3.1.1 Operability

Capacity factor

Offshore wind capacity factors are changing with time, more so than for other technologies, due to increases in the height and capacities of installed turbines. As height increases, so does wind speed [297]; thus newer, higher-capacity turbines provide higher capacity factors than smaller, older ones. As a result, a central value of 30% is adopted despite this being slightly higher than the 2005-2009 average of the UK fleet (27.6% [130]). The lower value of 25.6% is the worst UK fleet average from that time period, while the upper bound of 40% is the achievable value expected for new build.

Availability factor

Availability factors of offshore wind farms in the UK are not widely available. Therefore, the central figure used here is based on figures published for four large offshore wind farms in the UK: Kentish Flats (90 MW), Scroby Sands (60 MW), North Hoyle (60 MW) and Barrow (90 MW) [303-312]; it represents the average availability for the period 2005-2008. The lower estimate of 67% is the lowest value recorded by any of these farms, while the higher estimate of 98% is that suggested by RenewableUK for modern installations [313].

Technical and economic dispatchability

As discussed in Section 3.2.1.1, technical dispatchability is based on the ranking of a technology according to technical criteria. Wind power is not considered dispatchable because the output of a wind farm cannot be increased at will. Accordingly, wind assumes the worst rank for each technical dispatchability criterion.

The data for economic dispatchability, estimated as a ratio of capital and total levelised costs, are based on the cost estimates described further below.

Lifetime of fuel reserves

As a fuel-free technology, wind output is not affected by fuel reserves. The lifetime of the wind resource is effectively infinite, being limited only by the longevity of Earth's atmosphere (several billion years).

7.3.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

As discussed in Section 3.2.1.2, flexibility reflects the ability of each technology to provide trigeneration, net negative CO_2 emissions and high temperature (800°C) H_2 production. Ten points are accrued for each of the three criteria, with the sum being squared and divided by operational lifetime. The data for offshore wind power (shown in Table 28) reflect that fact that wind power provides no heat and cannot be used for carbon capture and storage (therefore cannot provide net negative CO_2 emissions).

Table 28: Data on the technological lock-in resistance of offshore wind power

Tri-generation	no
Net negative CO_2 emissions	no
Thermochemical H_2 production	no
Lock-in index score (0-30)	0
Lifetime (yrs)	20
Total score (f^2/l)	0

7.3.1.3 Immediacy

Time to plant start-up

The central estimate is the average construction time of the UK's five biggest offshore wind farms as of 2010 (Lynn and Inner Dowsing (194 MW), Kentish Flats (90 MW), Scroby Sands (60 MW), North Hoyle (60 MW) and Barrow (90 MW) [314]). These were chosen as they represent the most complete dataset of UK wind farms. The lower and upper bounds are the shortest and longest construction times of the same five installations.

7.3.1.4 Levelised cost of generation

Capital, operational, fuel and total levelised costs

As for the previous three options, cost estimates for offshore wind are based on those by Mott MacDonald [201] at 10% discount rate. They therefore inherit most of the assumptions made there, such as plant lifespan and average capacity factor. However, these assumptions are broadly in line with those used in the rest of the assessment in this study. Any subsidies are excluded from these costs, including the carbon price applied by Mott MacDonald. The cost data are summarised in Appendix 3. As mentioned in Section 4.3.1.4, the values used in this study have been verified against earlier UK cost estimates [118, 202] as well as data for other OECD countries published by IEA [99, 113] and MIT [119], but these data are not included due to obsolescence and inappropriate country-specificity.

7.3.1.5 Cost variability

Fuel price sensitivity

Wind power is fuel-free and therefore has a fuel price sensitivity of zero.

7.3.1.6 Financial incentives

Financial incentives and assistance

Offshore wind power currently receives two Renewable Obligation Certificates (ROCs) per megawatt-hour generated. It also effectively avoids the carbon tax imposed by the EU Emissions Trading Scheme. The effect of this is shown in Table 29.

Table 29: Financial incentives for offshore wind power

Number of ROCs received per MWh	2.00
Value per ROC 2011/12 (£)	38.69
Total ROC incentive (£/MWh)	*77.38*
Value of FiT [a] for <4 kWp in 2011/12	
new build £/MWh)	0
retrofit (£/MWh)	0
Total average FiT incentive (£/MWh)	*0*
Avoided emissions relative to CCGT (t CO_2/MWh)	0.4
Total avoided carbon price[b] (£/MWh)	*5.08*
TOTAL (£/MWh)	**82.46**

[a]Wind energy does not benefit from the Feed-in Tariff (FiT) due to its large size
[b]Average carbon price from April 2010 to March 2011: £12.69/t CO2 [203]

7.3.2 Environmental data and assumptions

The indicators used for the environmental assessment are shown in Table 2. The key assumptions and data sources are summarised below.

7.3.2.1 Material recyclability

Recyclability of input materials

Material recyclability is the percentage of materials used for construction of a power plant that can potentially be recycled. For most construction materials, the potential recyclability is 100%. The main exception to this is concrete, which is calculated to be 79.4% recyclable [based on 204][28]. Recyclability is calculated using the amounts of construction materials included in the model. In this case, the model is based on a farm of 3 MW turbines [315]. A capacity of 3 MW has

[28] Concrete is typically crushed into aggregate, which may then be used to manufacture new concrete by adding new cement. In the Ecoinvent v2.2 database [204] concrete contains 1890 kg of aggregate per 2380 kg concrete (= 79.4%).

been selected as this is currently the most common class of turbine being installed offshore in the UK [see 300].

The central estimate for the recyclability of offshore wind is, as illustrated in Table 30, 99.4%. The lower bound of the estimate (80.3%) corresponds to the amount of material that would be recycled at current UK demolition rates (see Section 4.3.2.2, Table 9).

Table 30: Major materials used for plant construction and their end-of-life recyclability for an offshore wind farm of 3 MW turbines [315]

Material	Amount (t)	Recyclability (%)
Cast iron	23.67	100
Chromium steel 18/8	41.16	100
Low-alloyed steel	359.25	100
Copper	35.32	100
Aluminium	10.62	100
Zinc	13.23	100
Lead	39.25	100
High-density polyethylene	0.021	100
Polyvinylchloride and other plastics	35.66	100
Glass-fibre reinforced plastic	21.00	100
Gravel	2.58	100
Concrete	17.85	79.4
Total materials	*599.6*	
Total recyclability of the plant		**99.4% (595.9 t)**

7.3.2.2 Other environmental issues

Environmental (LCA) impacts

The data for offshore wind are, in the central case, taken from a model of a large offshore wind farm comprising 3 MW turbines [315]. Turbine capacity of 3 MW is representative of new build in the UK, as mentioned above. The assumed capacity factor is 30% and the foundations are assumed to be of the steel monopile type. The current UK electricity mix is used for all relevant life cycle stages carried out it the UK.

Sensitivity analyses were also carried out to estimate the lower and upper bounds for the environmental impacts. As part of these analyses, the effect of end-of-life recycling of all major components was explored by adapting the central model to include current UK demolition recycling rates (see Table 9, Section 4.3.2.2). This contrasts with the assumption used in the central model in which end-of-life recycling is not considered. Note that in the case of offshore wind, the treatment of end-of-life recycling assumes that a sixth of the low-alloyed steel (corresponding to almost 60 tonnes) is left in the seabed and is therefore not recycled. This is in line with current practices for decommissioning offshore wind farms, where the foundations are typically cut off above the seabed to avoid unnecessary disruption to benthic life as well as excessive cost (see, for example, the decommissioning plan for Greater Gabbard offshore wind farm [316]).

Additional sensitivity analyses considered variations in capacity factor and individual turbine capacity as follows:

- turbine capacity varied from 2 to 5 MW to encompass all turbine capacities currently deployed and under construction in UK waters [300]; and
- capacity factor varied from 30% to 50% to encompass both expected and exceptional performance (see Section 7.3.1.1).

Greenfield land use

The indicator addresses only the operational stage, during which offshore wind farms do not occupy land. Note that small areas will be required on land for connection to the grid, but these are assumed negligible.

7.3.3 Social data and assumptions

The indicators used for the social assessment are shown in Table 2. The data sources used are discussed below.

7.3.3.1 Provision of employment

Direct and total (including indirect) employment

To enable comparison with the other assessed technologies, wherever applicable the same data sources have been used for offshore wind. Therefore, employment related to the extraction of ores and aggregates (for manufacture of concrete, steel and other metals) has been calculated based on material requirements specified in Ecoinvent [204] and employment data from BHP Billiton [216] and the Mineral Products Association [217]. The processing of raw materials into metals is based on labour data from Corus [218].

Employment due to manufacture of turbine components is based on the production workforce of Vestas averaged over the years 2006-2010 and the capacity of turbines produced by the company over the same time period [317-321]. This source has been selected because, as well as providing a complete dataset, Vestas have more installed capacity than any other manufacturer in offshore wind farms [300]. Results for the erection and operational stages were then derived from RenewableUK's 2010 assessment of UK-wide employment in the offshore wind installation and O&M sectors, respectively, and the electrical capacity being installed or operated in the same year [322]. As is the case for all technologies assessed in this research, maintenance employment only includes inspection and installation of replacement parts; employment owing to the manufacture of parts is excluded.

Due to a lack of available estimates in the literature, employment during decommissioning is assumed to be 20% of construction employment, in line with the other technologies assessed in this work. This is based on the approximate ratio of decommissioning cost to construction cost (see Section 4.3.3.1). However, offshore wind farms are expected to have lower decommissioning costs than, for example, nuclear plants [99], so this may be an overestimate. On the other hand, the fact that much of the decommissioning work will occur offshore may offset this to some extent.

Direct employment is estimated from the above by including only the erection, operation and decommissioning stages (i.e. excluding raw material extraction and processing as well as component manufacture).

7.3.3.2 Human health impacts

Worker injuries

The number of person-years of employment for each life cycle stage is used to calculate the number of expected injuries using Health and Safety Executive data [151] appropriate for the respective type of labour, as shown in Table 31. Note that injury rates for the ‘extractive and utility supply’ sector were used for the erection and decommissioning stages as opposed to the construction sector figures used in those stages for other technologies. This higher rate is intended to reflect the increased risk of offshore labour given the lack of specific data for that sector: the extractive sector statistics include work occurring on oil and gas platforms as well as transport to and from those platforms; activities with risks assumed to be similar to offshore wind farm maintenance.

Table 31: Injury rates used to calculate worker injuries in the offshore wind life cycle [151]

Life cycle stage	HSE sector-specific injury rate used	Number of injuries per 100,000 workers
Manufacture of wind farm		
extraction of ores/aggregates	Other mining	859.6
processing	Manufacturing (total)	811.8
manufacture of components	Manufacturing (total)	811.8
Erection	Extractive and utility supply (total)	1,117.1
Operation	Electricity, gas, steam and hot water supply (total)	553.8
Decommissioning	Extractive and utility supply (total)	1,117.1

Human toxicity potential & Human health impacts from radiation

These two impacts are estimated as part of life cycle assessment (see Section 7.3.2.2).

7.3.3.3 Large accident risk

Fatalities due to large accidents

As for the other technologies in this study, large accident fatalities are based on data from the Paul Scherrer Institut [221] drawing on their Energy-Related Severe Accident Database (ENSAD) [222, 223]. In ENSAD, large accidents are defined as those causing at least five fatalities. These results represent present-day Swiss conditions, but are likely to be equally appropriate for the UK as any wind related accident would be localised to the immediate area and affect only workers, making location irrelevant.

7.3.3.4 Local community impacts & Human rights and corruption

These impacts have not been considered, as they are company-specific and therefore cannot be assessed at the generic technology level.

7.3.3.5 Energy security

Avoidance of fossil fuel imports & Fuel supply diversity

As described in Section 3.2.3.6, the amount of imported fossil fuel potentially avoided is based on the average efficiency of the current UK fossil fuel fleet [calculated from 16], assuming that a unit of electricity generated by non-fossil capacity displaces a unit generated by fossil capacity. The methodology of the diversity of fuel supply indicator is also described in the above section but, as wind power is fuel-free, it is not subject to fuel supply disruption and has therefore been assigned the maximum score in the diversity of fuel supply indicator.

Fuel storage capabilities

The fuel storage capability indicator, measured as volumetric energy density, is intended to reflect the inherent resilience conferred by being able to store the potential to generate electricity, providing a hedge against any physical, economic or political disruption. Wind has zero fuel storage capabilities because, despite the wind itself having a derivable energy density, it cannot be stored and therefore does not contribute to the same goal. It is possible to partially overcome this by storing electricity (for example via pumped storage, batteries or hydrogen) but this approach is equally applicable to any other technology so cannot be considered an attribute of wind power.

7.3.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

This indicator is not applicable to the wind power life cycle (for further description see Section 3.2.3.7). Thus, wind power is assigned a score of zero.

7.3.3.7 Intergenerational equity

Abiotic resources (elements and fossil fuels)

These indicators have been estimated as part of LCA (see Section 7.3.2.2).

Volume of radioactive waste and liquid CO_2 for storage

This indicator is not applicable to the wind power life cycle (for further description see Section 3.2.3.8), so it is assigned a score of zero.

7.4 Results and discussion

This section presents the assessment results for the offshore wind option. The summary results are shown in Figure 23, Figure 24 and Figure 25; full results can be found in Appendix 3.

7.4.1 Techno-economic sustainability

This sub-section addresses the techno-economic assessment of offshore wind power. The results are presented in Figure 23 and discussed below.

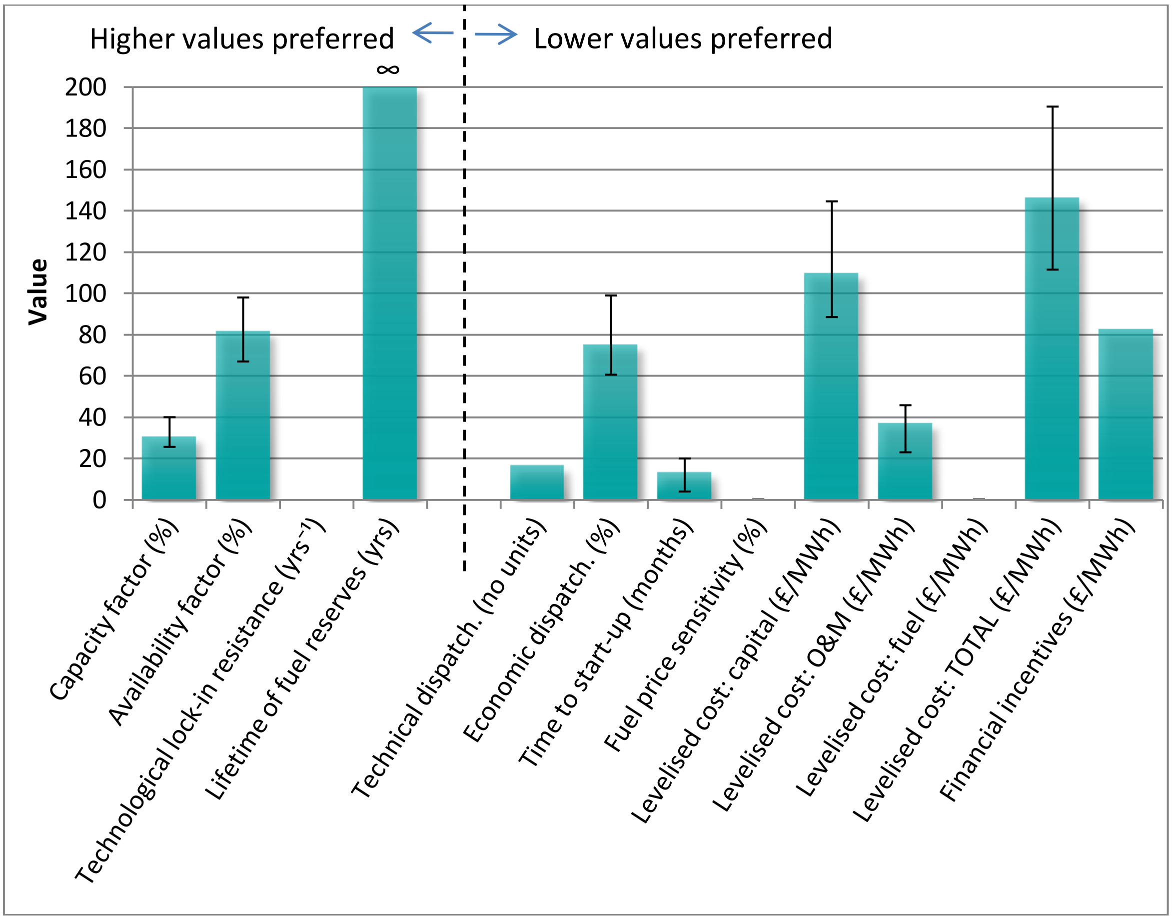

Figure 23: Techno-economic sustainability of offshore wind power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases. The *lifetime of fuel reserves* for wind power is effectively infinite. For full results, see Appendix 3**.**

7.4.1.1 Operability

Capacity and availability factors

As shown in Figure 23, there is a marked difference between the capacity factors and availability factors of offshore wind farms (30% and 81%, respectively), reflecting the fact that their output is constrained by wind speed. However, the analysis of Scroby Sands, Kentish Flats, Barrow and North Hoyle wind farms carried out in this study shows that the average availability of 81.4% compares badly to the 98% claimed by RenewableUK [313], suggesting that current offshore wind farms are underperforming. The worst observed availability factor was as low as 67% (Barrow wind farm, 2006; [312]). However, this may improve as knowledge and expertise are gained in maintaining this relatively new technology. The current capacity factors of around 30% (25.6-40%) will also increase as turbines grow in size, exploiting the stronger, steadier winds at higher altitude [297].

Technical and economic dispatchability

Wind power is inherently non-dispatchable as output cannot be controlled (apart from shutting down turbines in high wind speeds). As a result, it is assigned the worst possible score, 16, for the technical dispatchability indicator (compared to 4.7 for coal, with lower values being preferable (Section 6.4.1.1). Even if wind output could be controlled, it would not be economic to do so due to fact that 75% (in a range of 60.6-99%) of total levelised cost is capital: similarly to nuclear power, such a significant initial investment strongly incentivises operators to maximise electrical output in order to reduce payback time.

This lack of dispatchability poses problems in terms of grid management: the greater the proportion of national electricity supplied by variable sources like wind power, the more difficult it becomes to match supply to demand without resorting to expensive energy storage and/or back-up capacity. However, recent studies suggest that, while the costs and complexity of balancing the grid will increase proportionately with wind penetration, this increase is modest enough to allow wind power to expand to several times its current capacity without significant problems [see, for instance, 323, 324]. National Grid, for example, estimates that if total wind capacity increases by a factor of 5 (from 5.8 to 30.6 GW) only a 70% increase in average operating reserve capacity[29] would be required [324]. Thus the dispatchability problem should not be a significant barrier to wind deployment for the next decade or two.

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[29] Operating reserve requirement describes the unused capacity needed on the grid to balance out predicted short-term changes in demand or supply. Plants providing this spare capacity are required to generate the full amount at

Lifetime of global fuel reserves

Wind power is a fuel-free technology, meaning its 'fuel reserves' are effectively infinite.

7.4.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

This indicator accounts for future changes in energy use by considering whether an electricity technology could be modified to tri-generate electricity, heating and cooling, to have negative global warming potential or to produce hydrogen at high temperatures. Wind cannot provide any of these services and therefore scores zero. It is possible to use wind-generated electricity to produce hydrogen by hydrolysis, and this may be a route to overcoming the dispatchability problem discussed above by using excess power (at times of high wind and low electrical demand) to produce hydrogen. However, this hydrogen production method is equally applicable to any other electricity generating technology and cannot therefore be assigned to wind power alone.

7.4.1.3 Immediacy

Time to start up

Shorter construction periods minimise uncertainty and pay-back period. In this respect, wind power performs relatively well, with farms typically completed in four to 20 months depending on size (for instance, the 90 MW Barrow and Burbo Bank wind farms were built in 11 and 15 months, respectively [314]). The central estimate is 13 months, as shown in Figure 23. However, this speed is partly due to the smaller capacity of offshore wind farms relative to conventional plants. Nevertheless, as wind farms are modular, comprising many individual turbines, some power is normally exported to the grid long before the whole farm is completed. In this respect, electrical output can be increased in a very short period of time, albeit by small amounts.

7.4.1.4 Levelised cost of generation

Capital, operational, fuel and total costs

The costs shown in Figure 23 exclude any incentives provided by market mechanisms, which are discussed separately in Section 7.4.1.6. They are not, therefore, the net costs paid by owners. At

four hours' notice. The reserve requirement in 2011/12 was 4.78 GW. National Grid estimate this will increase to 8.13 GW in 2025/26 when wind capacity is expected to reach 30.6 GW [324].

10% discount rate, the offshore wind option costs 11.2-19.1 pence/kWh with a central estimate of 14.6 pence/kWh. This is approximately twice the cost of natural gas power and 55% higher than the central estimate for nuclear power.

The cost distribution is quite similar to that of nuclear power, being 75% capital and 25% operational. However, the lack of fuel costs mean that the total cost of electricity from wind farms is relatively stable (aside from unforeseen maintenance costs). This contrasts strongly with gas, where 75% of the cost is due to the fuel and less than 20% due to the cost of the power plant [99]. Similarly to nuclear power, the large capital component of wind power poses a problem in an uncertain market as it exposes owners to greater losses if plant lifetime is cut short or if future revenue decreases for any reason. The latter is particularly relevant for wind farms, as a large proportion of revenue comes from subsidies which could conceivably be withdrawn. To account for the relative risk of wind power, it is likely that a potential investor would assess this option at higher discount rates than, for example, gas power, increasing its apparent cost. This would be an attempt to illustrate the higher risk premium and, correspondingly, higher return on investment required to make wind profitable.

7.4.1.5 Cost variability

Fuel price sensitivity

Wind power is fuel-free and thus has no fuel price sensitivity. This decreases exposure to the risks posed by volatile fuel prices which are a significant problem for fossil-fuel options in general and gas power in particular (see Section 5.4.1.5).

7.4.1.6 Financial incentives

Financial incentives and assistance

The quantification and results of this indicator are discussed in Section 7.3.1.6 (see Table 29). From this, it is clear that the main incentive for prospective wind farm developers is the Renewables Obligation Order [12], which currently awards two certificates for every megawatt-hour of electricity generated from offshore wind farms (compared to one certificate for onshore wind). The effect of this is a subsidy of £77.38/MWh, paid for by utility companies and ultimately consumers. Offshore wind farm owners also benefit by avoiding the carbon tax set by the EU Emissions Trading Scheme, but this currently has a limited impact on the financial viability of low carbon technologies: at the 2010/2011 average of £12.69/tCO_2 [203], wind power avoids

£5.08/MWh in carbon taxes. Thus the total incentive for offshore wind power is £82.46/MWh, which equates to over 55% of its levelised cost (dependent on discount rate).

The recently announced 'contract-for-difference'[30] will directly subsidise producers of low-carbon electricity by guaranteeing them a set sale price [28]. However, this is not included here as its potential cost is currently unclear.

7.4.2 Environmental sustainability

This sub-section addresses the environmental part of the sustainability assessment of offshore wind power. All environmental indicators, except for material recyclability and greenfield land use, have been estimated using life cycle assessment (LCA) and the CML 2001 impact assessment methodology (the November 2009 update) [59, 139]. GaBi v4.4 LCA software [244] and the Ecoinvent v2.2 database [204] have been used for these purposes. The central estimates are based on modelling by Kouloumpis and Azapagic [315] of a farm of 3 MW wind turbines with steel monopile foundations and 30% capacity factor. The possible range of values includes figures from modelling conducted in this study (see Section 7.3.2.2) as well as the following models from other sources:

- two farms of 2 MW turbines, one at 30% capacity factor and one at 50% capacity factor [315];
- a farm of Bonus 2 MW turbines, adapted from Ecoinvent [204] as part of this work, with the UK electricity mix being used at all relevant life cycle stages; and
- two farms of 5 MW turbines, one at 30% capacity factor and one at 50% capacity factor [315].

The results are presented in Figure 24 and discussed below.

[30] The 'contract-for-difference' mechanism is essentially a long-term sale price guarantee, with the caveat that any revenue exceeding the set price (or 'strike price') is paid back to the government. For instance, a generator with an agreed strike price of 7 p/kWh is guaranteed that income – if the electricity is sold for 4 p/kWh, the government pays the generator the remaining 3 p/kWh – but if the generator sells for 8 p/kWh, the extra 1 p/kWh is paid back to the government [28].

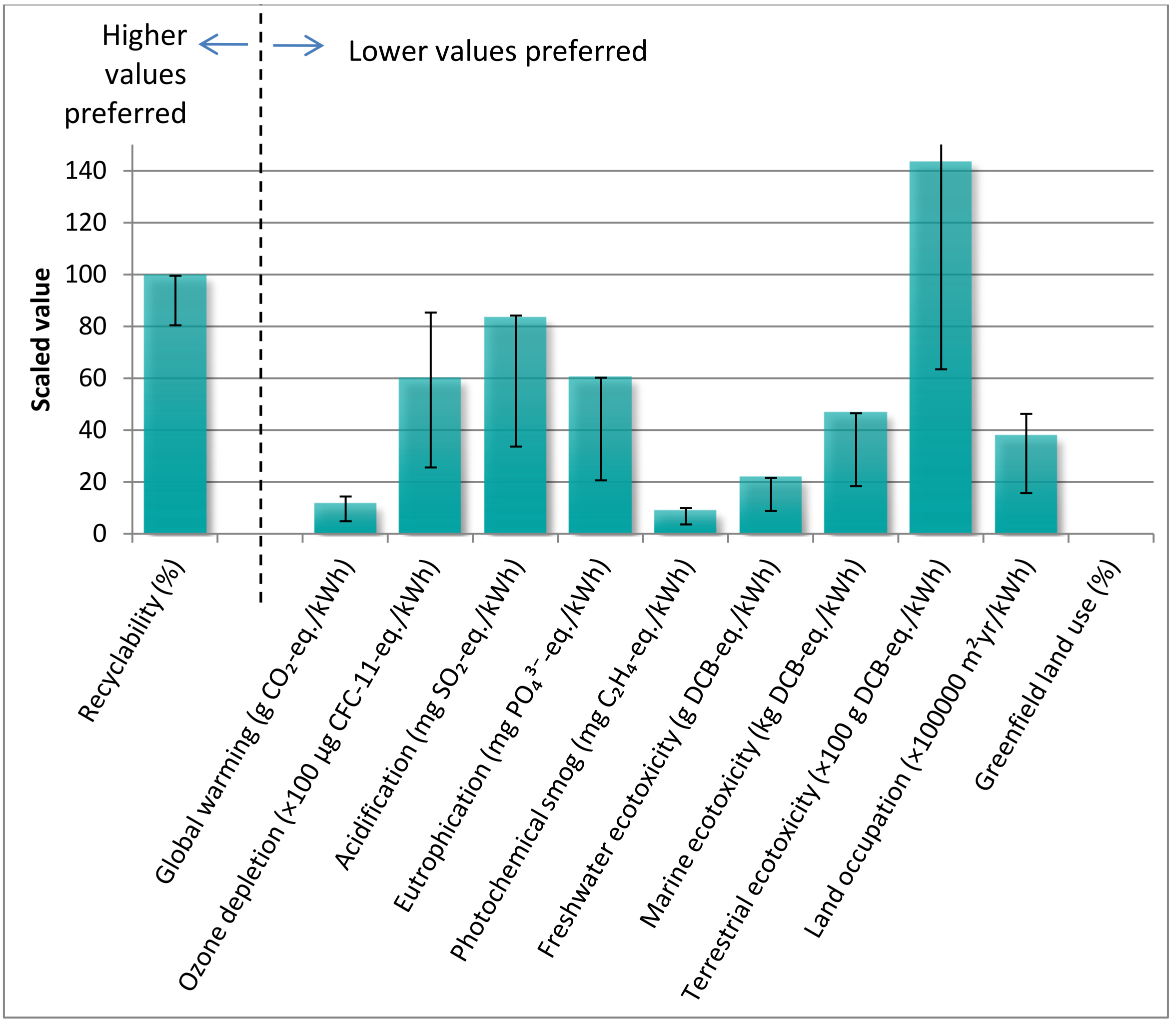


Figure 24: Environmental sustainability of offshore wind power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled by multiplying or dividing their original values by the factors shown in brackets. Bar height represents the central estimate in all cases. The upper value of the estimate for *land eco-toxicity* is 1.93 g DCB eq./kWh (193 on the graph's scaled *y* axis). For full results, see Appendix 3.

7.4.2.1 Material recyclability

<u>Recyclability of input materials</u>

Figure 24 (and Table 30 in Section 7.3.2.1) shows that the potential recycling rate of a wind turbine with a monopile foundation is very high at 99.4%. However, in reality it is unlikely that such high recycling rates are achievable. Decommissioning an offshore wind farm typically involves leaving a mass of steel in the seabed to reduce cost and minimise disruption to benthic life (see, for example, the Greater Gabbard wind farm decommissioning scheme [316]).

Sensitivity analysis shows that, when the above steel is excluded from recycling, and when current UK demolition recycling rates are used, the recyclability of offshore wind is 80.3%. Table

32 illustrates the reductions in environmental impacts that this achieves relative to the central model in which no recycling occurs. This shows that, even when taking into account the fact that a large mass of the foundations cannot be recycled as discussed above, recycling reduces all life cycle environmental impacts significantly. This is in stark contrast with end-of-life recycling of conventional plants such as coal, gas and nuclear, which is of limited benefit (see Table 13, Table 20 and Table 27). The reason for this is simply that the vast majority of environmental burdens created by wind power are due to manufacture of components (see Appendix 3 for full results by life cycle stage).

Table 32: Percentage reduction in impacts due to recycling of offshore wind turbine components at end-of-life, using current UK recycling rates

Impact	**Reduction of impact at current UK recycling rates[a] relative to no recycling (%)**
Global warming potential	28.56
Ozone depletion potential	19.19
Acidification potential	44.02
Eutrophication potential	65.87
Photochemical smog potential	42.44
Freshwater eco-toxicity potential	48.85
Marine eco-toxicity potential	59.37
Terrestrial eco-toxicity potential	27.99

[a] Aluminium 95%, other metals 99%, plastics 26%, concrete 71.5%, fibre cement facing tile 0%, paper 69%, gravel 30%, glass fibre reinforced plastic 10%, ceramic tiles 64%, insulation 18%, glass 0% (see Section 4.3.2.2).

7.4.2.2 Global warming potential (GWP)

As shown in Figure 24, the central estimate for the GWP of offshore wind power is 11.2 g CO_2 eq./kWh, with a range of 4.7-14.2. This is similar to other present-day estimates for offshore wind in literature: for example, 10 g CO_2 eq./kWh (PSI [246]); 5.2-13 g CO_2 eq./kWh (POST [293]). The GWP of offshore wind is close to that of nuclear power (6.4 g CO_2 eq./kWh) and around 34 times lower than the figure for gas power (379 g CO_2 eq./kWh). For reference, the current average GWP from the UK electricity mix is 584 g CO_2 eq./kWh [204].

The majority of this impact (90%) is caused by the manufacture of components (turbines, foundations and related equipment), mostly attributable to steel production.

7.4.2.3 Ozone layer depletion potential (ODP)

Offshore wind power has an ODP of 0.60 μg CFC-11 eq./kWh in the central case, with a minimum and maximum of 0.26 and 0.85, respectively. As is the case for GWP, 90% of this impact is due to component manufacture, with 39% due to the production of steel alone. This is primarily caused by usage and leakage of Halon 1301 and 1211, both of which are fire and explosion suppressants, during the production and transportation of the natural gas and oil used during metal production. However, the overall impact is comparable to nuclear power and an order of magnitude lower than the results for gas and coal power.

7.4.2.4 Acidification potential (AP)

Offshore wind life cycle AP is estimated at 0.083 g SO_2 eq./kWh (within a range of 0.034-0.084). Again, this impact is low, comparing to 1.78 g SO_2 eq./kWh emitted by the coal power life cycle (see Section 6.4.2.4). The principle cause of the impact, accounting for 96.4%, is emission of SO_2 and NO_x during the production of metal components.

7.4.2.5 Eutrophication potential (EP)

The offshore wind life cycle emits 0.060 g PO_4^{3-} eq./kWh in the central estimate. This is the highest value in the range of offshore wind models considered, with the result falling to 0.021 g PO_4^{3-} eq./kWh if end-of-life recycling occurs. The central estimate is comparable to the gas power life cycle which emits 0.062 g. Almost 90% of the impact is due to short- and long-term emissions of phosphates to freshwater, occurring primarily in the copper production chain.

7.4.2.6 Photochemical oxidant creation potential (POCP)

The central estimate of POCP is 0.0085 g C_2H_4 eq./kWh with a range of 0.0035-0.0098, which is around 16 times lower than the impact of coal power (0.140 g C_2H_4 eq./kWh; see Section 6.4.2.6). Again, copper and steel production are the biggest contributors to this impact, in this case due to emission of SO_2 and non-methane VOCs.

7.4.2.7 Water eco-toxicity

Freshwater eco-toxicity potential (FAETP)

Offshore wind has a relatively high FAETP of 21.4 g DCB eq./kWh. This is similar to the impact of nuclear power (21.1 g DCB eq./kWh) and around eight times the impact of gas power (2.6 g DCB eq./kWh). Again, the copper and steel production chains are the main causes, together accounting for 84% of the total, primarily via emissions of metals such as nickel, beryllium and cobalt. The minimum impact shown in Figure 24 is 8.7 g DCB eq./kWh, which is achieved by large capacity (5 MW) turbines at high capacity factors (50%), as this allows more electricity to be produced per unit of metal required.

Marine eco-toxicity potential (MAETP)

The offshore wind life cycle has an MAETP of 18-46 kg DCB eq./kWh with 46 being the central estimate. This is comparable to the MAETP of nuclear power (40 kg DCB eq./kWh), but remains around seven times higher than the impact of natural gas power. The production chains of copper and steel are again the main causes, with 88% of the total being caused by emission of metals such as beryllium, nickel and cobalt to freshwater, which eventually has an impact on marine environments.

7.4.2.8 Land use and quality

Terrestrial eco-toxicity potential (TETP)

TETP is relatively high at 1.4 g DCB eq./kWh, as shown in Figure 24, with a range of 0.63-1.9. This is comparable to the impact of coal power (1.5 g DCB eq./kWh). Emission of chromium to air causes 83% of this impact, primarily resulting from stainless steel production. The lowest impact in the range is again achieved by 5 MW turbines at 50% capacity factor due to their lower steel requirement per unit electrical output: in this case, offshore wind is comparable to nuclear power (0.63 g DCB eq./kWh c.f. 0.74 for nuclear).

Land occupation

The life cycle of offshore wind power occupies 0.00016-0.00046 m^2yr/kWh with a central estimate of 0.00037. In contrast, a mining-intensive option like coal power occupies 73 times more land, with 99% of that occupation being by coal mines and associated infrastructure (see Section 6.4.2.8).

Greenfield land use

As discussed in Section 7.3.2.2, greenfield land use only considers the operational stage of the life cycle, at which point offshore wind occupies no land (apart from very small amounts required for onshore grid connections, which are considered negligible). Greenfield land use is therefore zero.

7.4.3 Social sustainability

This sub-section addresses the social part of the sustainability assessment of offshore wind power. The results are presented in Figure 25 and discussed below.

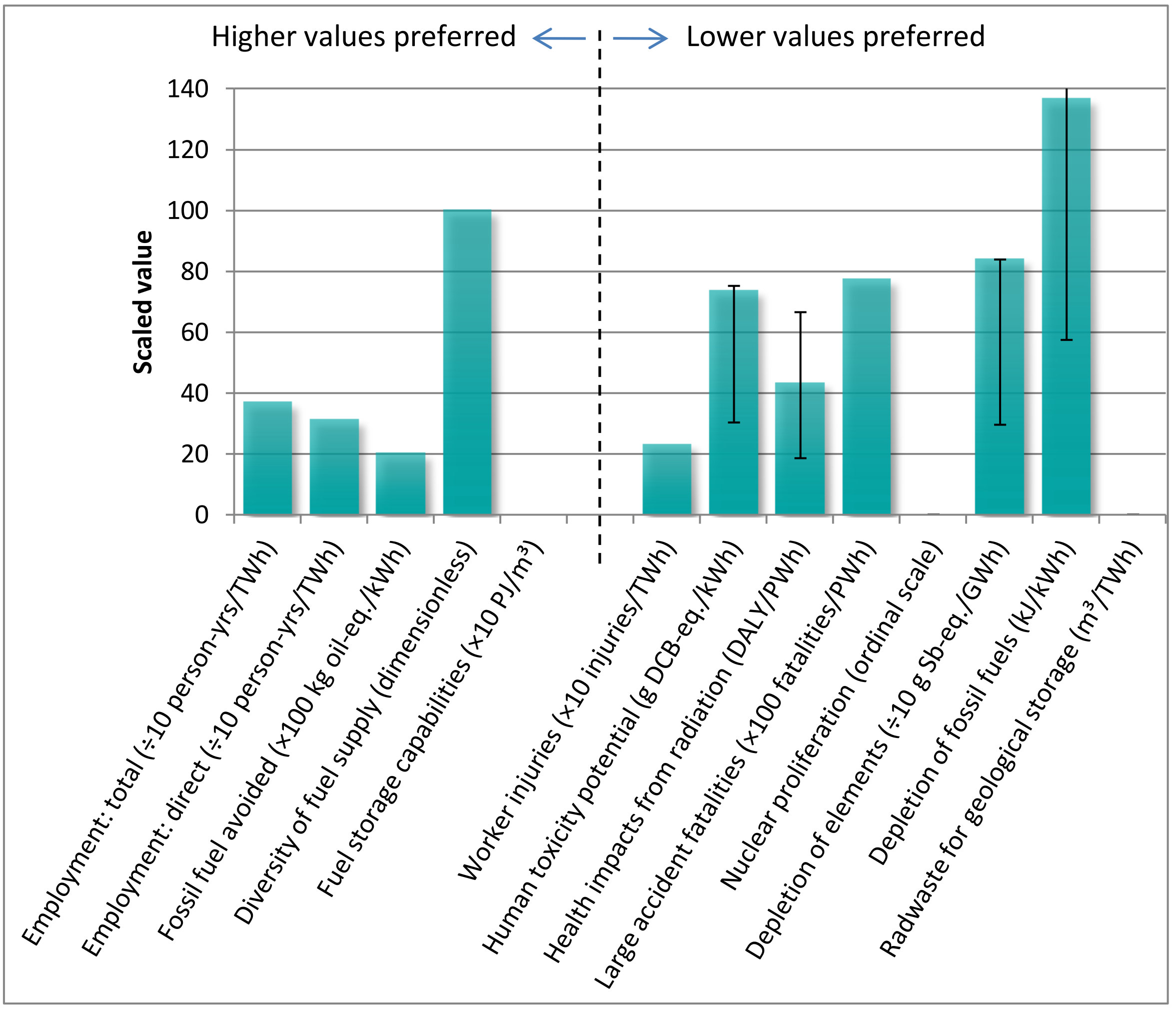


Figure 25: Social sustainability of offshore wind power. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases. The upper value of the estimate for *depletion of fossil fuels* is 174 kJ/kWh. For full results, see Appendix 3**.**

7.4.3.1 Provision of employment

Total employment

Total employment includes direct and indirect employment, with the former relating to the erection, operation, maintenance and decommissioning of the wind farm, and the latter to the raw material extraction and manufacturing stages. As shown in Figure 25, offshore wind power provides around 368 person-years of employment per terawatt-hour, most of which is direct. Approximately 79% of this employment is due to the operation and maintenance of the wind farm: in 2010 RenewableUK estimated that 527 people were employed in the UK to operate and maintain the 680 MW of offshore capacity installed at the time [322]. Based on the figures discussed in Section 5.4.3.1, a gas power plant of similar capacity would only provide around 60 jobs during the operational stage.

However, this high O&M employment suggests there may be a connection with the fact that several offshore wind farms in the UK have proved less reliable than expected (as discussed in Section 7.4.1.1). It may be the case that wind farm owners are currently trying to increase the availability of their turbines via more aggressive maintenance, and consequently higher employment. If this is the case, employment might be expected to reduce noticeably as production and operational experience improves.

Direct employment

As discussed above, O&M is the main provider of employment in the offshore wind life cycle. Consequently, excluding the indirect stages (raw material extraction and component manufacture) from the estimate has little effect on the employment result, with offshore wind still providing 311 person-years/TWh. As it is associated with the wind farm site itself, most of this employment will be in the UK.

7.4.3.2 Human health impacts

Worker injuries

An estimated 2.3 injuries/TWh are caused by the offshore wind life cycle, as shown in Figure 25. Around 70% of these injuries are expected to occur in the O&M stage of the life cycle and are simply a consequence of offshore wind's high employment provision.

Human toxicity potential (HTP), excluding radiation

As discussed earlier in reference to environmental toxicity impacts, the requirement of the offshore wind life cycle for large amounts of metals, particularly copper and steel, results in considerable emission of toxic metallic compounds to air and water. This also gives offshore wind a relatively high HTP of 30-75 g DCB eq./kWh (central estimate = 74), primarily due to arsenic, chromium and selenium. This result is lower than that of nuclear power (115 g, mainly from uranium mill tailings) and coal (78 g, mostly from aerial emissions during coal combustion), but an order of magnitude higher than the gas power result (5.4 g).

Total human health impacts from radiation

Radioactive substances emitted during the offshore wind life cycle cause 0.043 disability-adjusted life years (DALYs) per TWh (Figure 25) with a range of 0.019-0.067. This is a low impact, comparing to the 20.3 DALYs/TWh attributable to nuclear power (although even that figure is not high, as discussed in Section 4.4.3.2). The majority (92%) of offshore wind power's impact is again due to component manufacture. Counterintuitively however, the highest impact (0.067 DALYs/TWh) occurs when components are recycled at end-of-life: recycling of metals is achieved in electric arc furnaces whereas most primary steel is produced via basic oxygen steelmaking, therefore the recycling option has a higher electricity requirement, some of which will have been produced by nuclear power.

7.4.3.3 Large accident risk

Fatalities due to large accidents

As shown in Figure 25, estimates by the Paul Scherrer Institut indicate that offshore wind causes 0.77 fatalities/PWh [221]. While this estimate is not as low as that of nuclear power, it is 27 times lower than that of coal power. Additionally, individual accidents in the wind life cycle are extremely unlikely to cause more than 10 deaths (as opposed to the 49,000 potential fatalities caused by a nuclear accident). This greatly reduces the perceived danger of wind power.

7.4.3.4 Local community impacts and human rights & corruption

As mentioned in Section 7.3.3.4, these impacts have not been considered because they are company-specific and therefore not applicable for technology assessment. For further discussion, see Section 3.2.3.

7.4.3.5 Energy security

Avoidance of fossil fuel imports

The fossil fuel plants that currently provide around 75% of UK electricity are estimated here to use, on average, 200 tonnes of oil-equivalent (toe) per GWh (see Section 3.2.3.6). The avoidance of this by non-fossil capacity such as offshore wind represents a national increase in resilience to fossil fuel price volatility. However, it should be noted that wind power is non-dispatchable and variable in its output, therefore an increase in wind capacity will force the remaining fossil plants to operate less efficiently as they are increasingly needed to follow load. Consequently, the figure of 200 toe is likely an overestimate.

Diversity of fuel supply mix

This indicator reflects the resilience of national electricity production to fuel supply disruptions, whether they are economic, technical or political. However, as wind power is fuel-free, it is not subject to fuel supply disruption and has therefore been assigned the maximum score of 100 in the diversity of fuel supply indicator.

Fuel storage capabilities

Since wind power cannot be called upon to produce electricity unless the wind is blowing, the concept of fuel storage does not apply (see Section 7.3.3.5). Offshore wind has therefore been assigned a score of zero.

7.4.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

This is not applicable to wind power, so a score of zero has been assigned.

7.4.3.7 Intergenerational equity

Use of abiotic resources (elements)

The use of abiotic elements in the offshore wind life cycle is 0.30-0.84 kg Sb eq./GWh with a central estimate of 0.84 as shown in Figure 25. This is an order of magnitude more than coal, gas or nuclear power. Half of this impact is due to the use of lead in the fixed parts of the wind turbine (the nacelle, tower and foundations). The remainder is primarily due to depletion of copper (for wiring), chromium, molybdenum and zinc.

Use of abiotic resources (fossil)

Offshore wind power consumes 137 kJ/kWh of fossil resources. For comparison, this is less than one hundredth the amount used in the coal power life cycle (see Section 6.4.3.7). Over 90% of offshore wind's fossil fuel consumption is due to the extraction and processing of copper, lead, steel and zinc.

Volume of radioactive waste and liquid CO_2 to be stored

Offshore wind power does not produce radioactive waste or liquid CO_2 for storage.

7.5 Data quality in the offshore wind power assessment

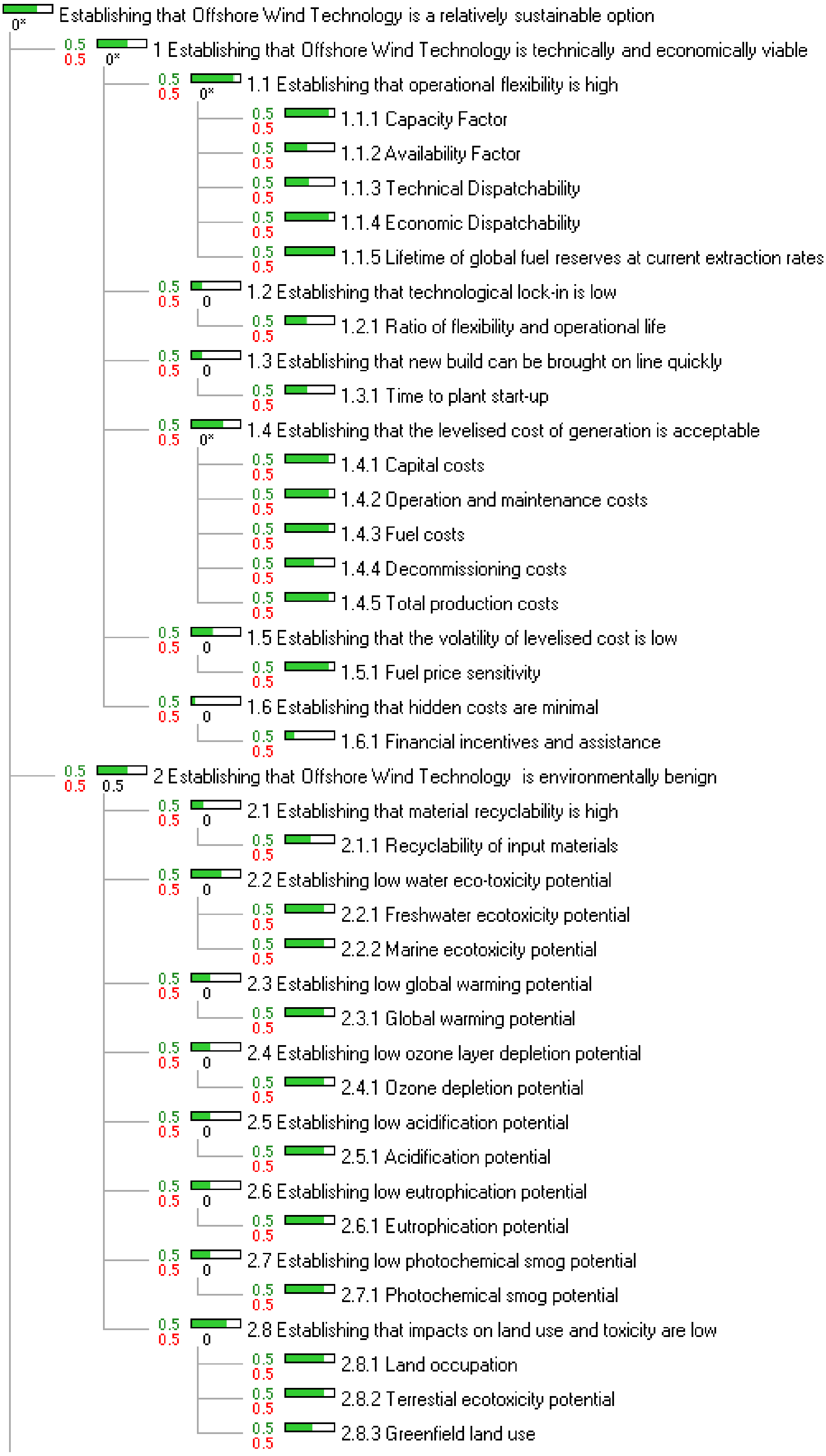
Data quality has been assessed using the same methodology as for the nuclear option and the other options assessed in this work (see Section 4.5 and Appendix 4).

Figure 26 summarises the data quality analysis. The overall assessment is rated at 69% (where a rating of 100% would indicate perfect quality). This is very similar to the ratings for nuclear power (66%) and natural gas power (68%), and for similar reasons.

The weakest of the three 'pillars' in this sustainability assessment is the environmental group, scoring 61.9%. The main reason for this is high dependency due to the LCA indicators sharing common data sources. Therefore, dependency between indicators is high, meaning confidence in the results of the group as a whole is reduced slightly. Additionally the *greenfield land use* indicator result is based on the judgment that any land used in connection with offshore wind farms (for example, for grid connections and substations) is negligible, meaning the results is rated as 'poor' against the 'data source' criterion.

Overall, the data quality of the offshore wind sustainability assessment is good given the purpose of this study: a generic assessment of offshore wind power as is currently being deployed in the UK. Improvements could be made by focusing on lower rated areas shown in Figure 26 as shorter green bars. Thus, the focal points of potential future work should include:

- improving the assessment of operability by including data on the availability of newer wind farms and by incorporating more complex assessment of wind power's dispatchability;
- improving financial incentives and assistance by extending the current data to include hidden subsidies as discussed in Section 3.2.1.6;
- improving the employment estimate by using figures specific to modern, offshore-only turbines throughout the life cycle; and
- improving the worker injury estimate by adding data specific to offshore wind farm installation and maintenance.


Establishing that Offshore Wind Technology is a relatively sustainable option
1 Establishing that Offshore Wind Technology is technically and economically viable
1.1 Establishing that operational flexibility is high
1.1.1 Capacity Factor
1.1.2 Availability Factor
1.1.3 Technical Dispatchability
1.1.4 Economic Dispatchability
1.1.5 Lifetime of global fuel reserves at current extraction rates
1.2 Establishing that technological lock-in is low
1.2.1 Ratio of flexibility and operational life
1.3 Establishing that new build can be brought on line quickly
1.3.1 Time to plant start-up
1.4 Establishing that the levelised cost of generation is acceptable
1.4.1 Capital costs
1.4.2 Operation and maintenance costs
1.4.3 Fuel costs
1.4.4 Decommissioning costs
1.4.5 Total production costs
1.5 Establishing that the volatility of levelised cost is low
1.5.1 Fuel price sensitivity
1.6 Establishing that hidden costs are minimal
1.6.1 Financial incentives and assistance
2 Establishing that Offshore Wind Technology is environmentally benign
2.1 Establishing that material recyclability is high
2.1.1 Recyclability of input materials
2.2 Establishing low water eco-toxicity potential
2.2.1 Freshwater ecotoxicity potential
2.2.2 Marine ecotoxicity potential
2.3 Establishing low global warming potential
2.3.1 Global warming potential
2.4 Establishing low ozone layer depletion potential
2.4.1 Ozone depletion potential
2.5 Establishing low acidification potential
2.5.1 Acidification potential
2.6 Establishing low eutrophication potential
2.6.1 Eutrophication potential
2.7 Establishing low photochemical smog potential
2.7.1 Photochemical smog potential
2.8 Establishing that impacts on land use and toxicity are low
2.8.1 Land occupation
2.8.2 Terrestial ecotoxicity potential
2.8.3 Greenfield land use

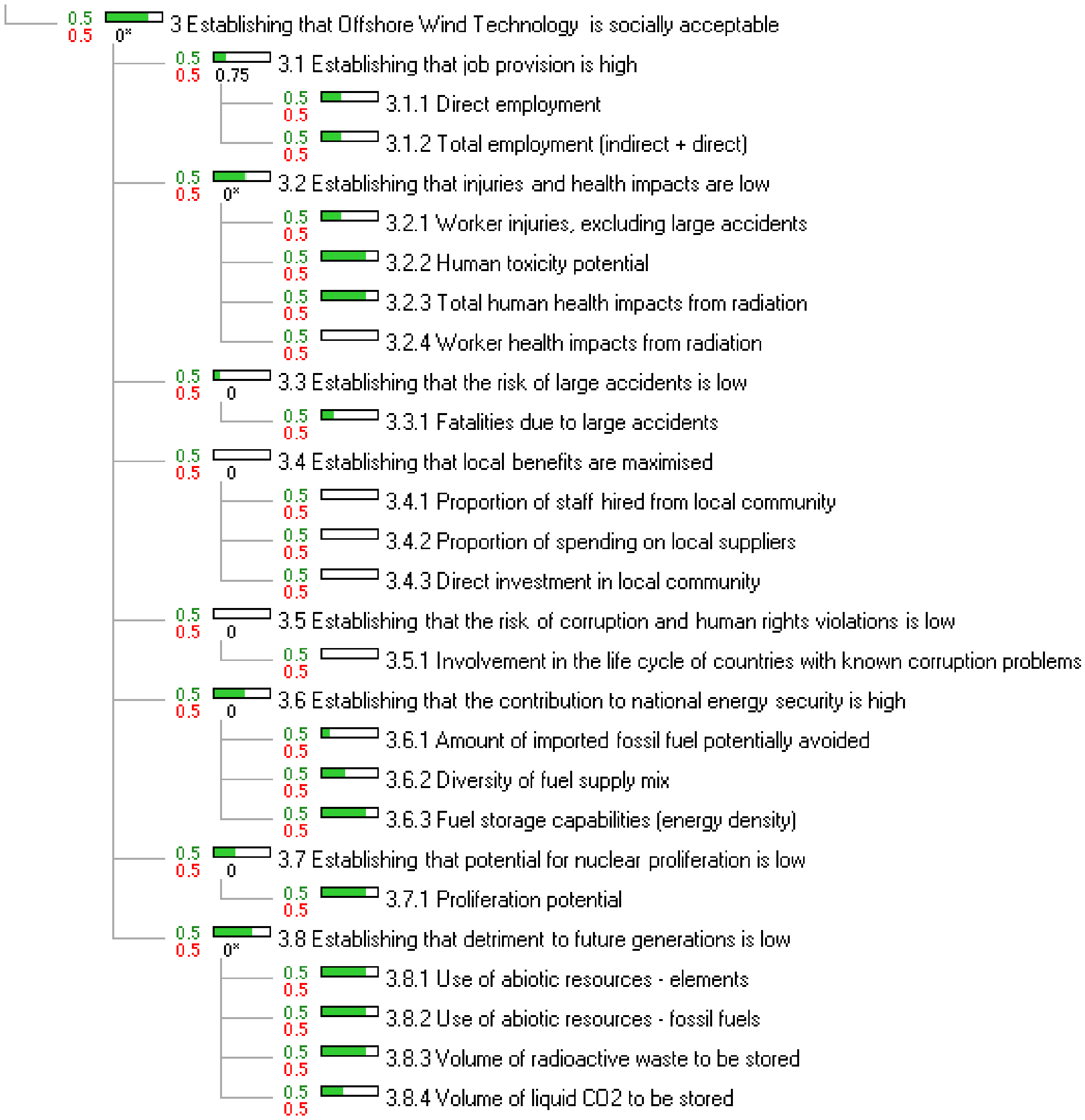


Figure 26: Data quality summary for the sustainability assessment of offshore wind power

7.6 Summary

The results of the sustainability assessment of offshore wind can be summarised as follows:

- An electricity mix with a large contribution from variable sources such as wind power is inherently difficult to manage as it is harder to balance supply and demand. However, this depends on the penetration of wind power and the composition of the electricity mix as a whole. It is thought that wind power's contribution can increase five-fold without necessitating more than a 70% increase in the average operating reserve capacity.
- The cost of offshore wind power is relatively high at 11.2-19.1 pence/kWh; approximately double that of gas power. Offshore wind farm owners currently receive an effective subsidy of 8.2 pence/kWh which offsets around half of the above cost. The cost of this subsidy is borne by electricity suppliers and is therefore likely to be passed to consumers indirectly via increased electricity prices.
- However, operation and maintenance costs currently account for around 25% of the total levelised cost, which is higher than might be expected for a fuel-free technology. This may be due to owners attempt to improve availability factors via increased maintenance, and can probably be expected to improve with experience. Additionally, the economic case for offshore wind depends heavily on capacity factors, which should improve as newer, larger turbines become widespread.
- Offshore wind is one of the best environmental options and broadly comparable to nuclear power in this respect. Global warming potential is low at 11 g CO_2 eq./kWh. Offshore wind does, however, have relatively bad freshwater and terrestrial eco-toxicity due to its high metal requirements.
- Provision of employment is high at 368 person-years/TWh, with the majority occurring in the operational stage (and therefore in the UK). While this does result in relatively high worker injury rates, this is simply a consequence of high employment. Total worker injury rates are still only around half that of the coal life cycle.
- Offshore wind, being fuel-free, increases energy security in some respects. However, this should be balanced against its lack of dispatchability and the increased grid-level reserve capacity this will eventually require.
- Offshore wind has few intergenerational equity issues, apart from non-fossil resource depletion due to its high metal requirements.

The next chapter focuses on the life cycle sustainability of solar photovoltaics.

8 Solar photovoltaics

In this chapter, the sustainability assessment framework is applied to solar photovoltaics (PV) from the perspective of current new build in the UK: it is therefore focused on residential-scale installations of approximately 3 kWp capacity. The chapter starts in Section 8.1 with an overview of the current situation with respect to solar PV in the UK. This is followed by a summary of the PV life cycle and its related sustainability issues in Section 8.2. The data sources and assumptions that were used in the assessment are described in Section 8.3, while Section 8.4 presents and discusses the results. Finally, Section 8.5 summarises the data quality analysis of this assessment.

8.1 Solar PV in the UK: the current situation

The average incident sunlight in the UK is approximately 100 W/m^2 [2]. With a land area of 242,900 km^2 [224], the total solar resource of the UK is therefore around 213,000 TWh per year: approximately 560 times national electricity consumption in 2010 [calculated from 5]. However, virtually none of this resource is currently exploited. Solar power is a relatively immature technology and its deployment in the UK depends largely on the level of subsidisation available.

The Feed-in Tariff (FiT) scheme, introduced in April 2010, is the current regulatory tool by which solar PV is subsidised: the FiT requires large energy suppliers to make payments to owners of small-scale (<5 MW) renewable installations, such as PV, based on the total amount of electricity produced [14]. This includes electricity both exported to the grid and consumed on site. In 2009, before the FiT was introduce, the total installed capacity of solar PV in the UK was 26.5 MW, which provided approximately 0.005% of electricity generated in that year [5]; as of 23rd April 2012, capacity had increased to 1044 MW [325] illustrating the impact of the FiT scheme. At the time of writing, electricity generation figures are not available for 2012, but 1044 MW should equate to around 0.2% of the electricity mix[31]. Thus, solar power's contribution is still very limited, despite its rapid growth.

The FiT rates have recently been cut by approximately half following a review by the Government [see 326] and it is not currently clear what effect this will have on PV deployment. However, even

[31] Assumes total electricity generation in 2012 of 380,000 GWh and a PV capacity factor of 8.6%: these figures are in good accord with published generation data for 2010 (381,000 GWh [5]) and expected UK capacity factors (see Section 8.3.1.1).

after this reduction, PV receives the highest subsidy of any electricity generating technology in the UK (see Section 8.4.1.6) and is generally expected to play an increasing role in the medium- to long-term outlook for the electricity mix [see, for example, 3].

8.2 Solar PV life cycle and sustainability issues: an overview

As shown in Figure 27, the life cycle of solar PV involves extraction of raw materials, manufacture, installation, operation and decommissioning of the panels. As for all mining and heavy industry processes, the major sustainability issues during the extraction of raw materials are worker safety and environmental impacts related to energy use, as well as leaching of toxic substances and depletion of abiotic resources. The raw material are used to manufacture PV cells, which are then used to create complete PV panels. This stage also includes the manufacture of any mounting brackets necessary to attach the panels to buildings, as well as other electrical equipment such as wiring and an inverter to convert DC to AC so that the panels' electrical output can be used in homes or exported to the grid. Manufacturing the many components required is energy-intensive and therefore associated with significant emissions to the environment. However, due to the large amount of materials and labour required relative to the electrical output, considerable employment can be generated by these stages.

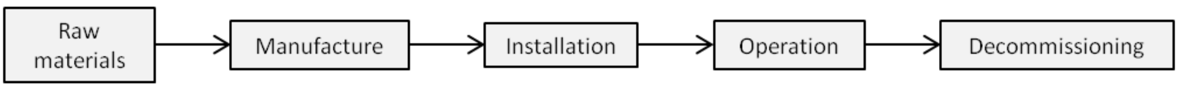


Figure 27: The life cycle of solar photovoltaics

Installation of a residential solar system typically takes a matter of days and is followed by an operational lifetime of around 25-35 years [327][32]. Larger, commercial-scale systems take longer to install, but are still relatively quick due to the fact that nearly all parts are prefabricated. However, the cost of solar PV panels is currently a major hindrance to their wider adoption, with investors relying heavily on subsidies to make this option financially viable.

The installation and operational stages of the life cycle provide labour opportunities, many of which are specialised and skilled. There are virtually no environmental impacts associated with

[32] There is no set lifespan for solar panels: electrical output simply declines with age. Manufacturers therefore base their warranties on a certain percentage of as-new performance being retained after a period of time, typically 25 years. Panels will, however, continue to produce some electricity for much longer than this.

the operational stage of the PV life cycle, aside from those resulting from the need to replace the inverter at some point during the life of the panels. This, and particularly the lack of GHG emissions at the operational stage, is the main reason for the government's promotion of solar PV via the Feed-in-Tariff. Like wind power, the output of solar PV is variable, meaning that dispatchability is a possible issue for consideration during the operational stage: as the capacity of PV connected to the grid increases, the ability of grid operators to balance supply and demand declines owing to the intermittency. However, as output is linked to sunlight and therefore follows a day-night cycle, it tends to fit electricity demand much more closely than the output of wind power.

Various sustainability issues associated with different parts of the solar PV life cycle are discussed further in the following sections, in conjunction with the related indicators. The indicators are, where possible, expressed per kWh electricity generated in order to enable equivalent comparisons between solar PV and other electricity options.

8.3 Data sources and assumptions

The key assumptions and data sources for the solar PV option are discussed below. Full results are given in Appendix 3. Wherever possible and available, a range of values for each option has been considered to establish the lower and upper bounds. Where appropriate, average values are used in the sustainability assessment. In other cases, 'central' estimates are used instead, representing the most likely values for new, residential solar PV installations.

8.3.1 Techno-economic data and assumptions

The indicators used for the techno-economic assessment are shown in Table 2. The data sources used are discussed below.

8.3.1.1 Operability

Capacity factor

Photovoltaic panels are rated at a given capacity by laboratory testing at 25°C and illumination of 1000 W/m^2. This latter figure is the average insolation received at the surface of the Earth on a clear day, perpendicular to the Sun (i.e. at the equator) [2]. Therefore, this capacity rating reflects the peak output of solar panels and so is expressed as kilowatts peak (kWp). Because of this system, the capacity factors achievable with solar PV are almost entirely dependent on the incident sunlight: all else being equal, panels with different efficiencies will not have different capacity factors (a more efficient 1 kWp panel is simply smaller than a less efficient 1 kWp panel). Given this rating system, it is possible to calculate the maximum theoretical capacity factor under UK conditions: the annual average insolation at an optimally inclined plane in the UK is 1111 kWh/m^2 [328], or 126.7 W/m^2, giving a capacity factor of 12.7% (= 126.7 W/m^2 ÷ 1000 W/m^2). However, this is not achievable in reality due to changes in the efficiency of panels at different ambient temperature and losses in the system, such as those due to conversion from DC to AC.

Real operational figures are provided by the UK PV Domestic Field Trial [329]: the outputs of UK installations were found to range from approximately 400 kWh/kWp to over 900 kWh/kWp, with the median category being 700-800 kWh/kWp. This same range is suggested for the UK in a Europe-wide study by Suri et al. [330]. A middle value of 750 kWh/kWp equates to a capacity factor of 8.6% (= 750 kWh ÷ (1 kWp × 8766 hours in a year)). Therefore, this is the value used as the central estimate in this assessment. Lower and upper estimates are also based on the UK PV Domestic Field Trial, taking 350 and 950 kWh/kWp to arrive at 4.0% and 10.8%, respectively. Note that very low reliability and a significant amount of shading of the panels would be required to achieve a figure as low as 4% [329].

Availability factor

No comprehensive dataset of UK availability factors is available. However, data have been reported by an IEA analysis of German, Swiss and Italian PV installations [331]. Systems installed after 1996 had an average availability of 95.9%, which is adopted here as the central estimate. Around 55% of the dataset in the above study achieved over 99% efficiency, which provides the upper estimate. Minimum availabilities were not reported (being described simply as '<90%'), meaning a lower estimate could not be made.

Technical and economic dispatchability

As discussed in Section 3.2.1.1, technical dispatchability is based on the ranking of a technology according to technical criteria. Like wind power, solar PV is not considered dispatchable because its output cannot be increased at will. Accordingly, it assumes the worst rank for each technical dispatchability criterion.

The data for economic dispatchability, estimated as a ratio of capital and total levelised costs, are based on the cost estimates described further below.

Lifetime of fuel reserves

As a fuel-free technology, solar PV is not affected by fuel reserves other than being constrained by the remaining lifespan of the Sun. At several billion years, fuel reserves are therefore effectively infinite.

8.3.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

As discussed in Section 3.2.1.2, flexibility reflects the ability of each technology to provide trigeneration, net negative CO_2 emissions and high temperature (800°C) H_2 production. Ten points are accrued for each of the three criteria, with the sum being squared and divided by operational lifetime, as shown below in Table 33. Solar PV does not produce any usable heat and cannot be used for carbon capture and storage (therefore cannot provide net negative CO_2 emissions). It therefore scores zero.

Table 33: Data on the technological lock-in resistance of solar PV

Tri-generation	no
Net negative CO_2 emissions	no
Thermochemical H_2 production	no
Lock-in index score (0-30)	0
Lifetime (yrs)	25
Total score (f^2/l)	**0**

8.3.1.3 Immediacy

Time to plant start-up

The central estimate is based on a three-day installation period for a typical residential solar system [327]. The upper estimate indicates the construction of a larger, utility scale system (70 MW, Rovigo, Italy [332]) as an indication of how construction times might compare to the larger power stations of other types assessed elsewhere in this work. However, it should be noted that such large PV installations are better able to exploit economies of scale than residential systems and will therefore have lower costs and environmental impacts than the central estimates in this study (see below).

8.3.1.4 Levelised cost of generation

Capital, operational, fuel and total levelised costs

Unlike the cost estimates for nuclear, coal, gas and offshore wind, cost figures for solar PV could not be based on Mott MacDonald [201] as they were not assessed there. A similar cost report by Arup [333], also conducted for the Department of Energy and Climate Change, did include solar PV estimates, but discounted costs were only reported for large-scale (>50 kWp) solar installations. Large-scale projects are cheaper than residential-scale installations due to economies of scale and greater purchasing power (i.e. the ability to negotiate lower prices for components due to bulk purchasing). Estimates of residential solar PV costs in this assessment therefore had to be calculated from non-discounted values given in the Arup report for smaller systems (<50 kWp), as follows:

- Discount rate: 10%
- Capacity factor: 9%
- System lifetime: 25 years
- Capital costs (£million/MW): 2732-5080 (median = 3339)
- O&M costs (£/MW/year): 16500-70700 (median = 24800)
- Decommissioning costs: assumed negligible, allocated to roof replacement

The discount rate selected is in agreement with cost estimates of other technologies in this work, while the capacity factor matches the approximate capacity factors discussed in Section 8.3.1.1. System lifetime of 25 years corresponds with the typical manufacturer warranty for solar panels [see 327], as well as the period over which Feed in Tariff (FiT) payments are received (see Section 8.3.1.6). The decision to ignore decommissioning costs is consistent with Mott MacDonald [201] and IEA [99] assumptions for non-nuclear technologies, in which costs are expected to be offset by the scrap value of the equipment. In this case, it is also likely that solar panels would only be removed when roof replacement is necessary, thus minimising the costs directly attributable by the panels. In any event, discounting future liabilities means that decommissioning costs are rarely substantial when viewed from the present (except in the case of nuclear power) [99, 201].

The resulting levelised costs were then validated by performing the same process on the undiscounted costs of all systems smaller than 50 kWp in OECD countries reported by IEA in 2010 [99]. The median cost estimate was within 7% of the result derived from the Arup data. Being in good agreement, the Arup results were then selected for use in this study as they are specific to the UK, whereas the IEA figures are based on Canada, Germany and the Netherlands. The final cost estimates are summarised in Appendix 3.

8.3.1.5 Cost variability

Fuel price sensitivity

Solar PV has a fuel price sensitivity of zero.

8.3.1.6 Financial incentives

Financial incentives and assistance

Solar PV currently receives support via the Feed-in Tariff (FiT), under which owners are paid by energy suppliers for each unit of electricity generated: owners of a residential PV system on a new property receive 37.8 pence/kWh; if the system is retrofitted to an older property, the FiT provides 43.3 pence/kWh. Once registered, a PV installation receives the tariff at the agreed rate for 25 years [334]. Like other technologies with zero carbon emissions at the point of electricity generation, solar PV also effectively avoids the carbon tax imposed by the EU Emissions Trading Scheme. The effects of this and the FiT are shown in Table 34. It should be noted that the FiT bandings have recently been revised following a review by the government, the consequences of which are discussed in Section 8.4.1.6.

Table 34: Financial incentives for solar PV

Number of ROCs received per MWh	0
Value per ROC 2011/12 (£)	0
Total ROC incentive (£/MWh)	*0*
Value of FiT for <4 kWp in 2011/12	
new build £/MWh)	378.00
retrofit (£/MWh)	433.00
Total average FiT incentive (£/MWh)	*405.50*
Avoided emissions relative to CCGT (t CO_2/MWh)	n/a[a]
Total avoided carbon price[b] (£/MWh)	*n/a*
TOTAL (£/MWh)	**405.50**

[a]Replacing large-scale CCGT with small-scale PV is not considered realistic, hence the avoided carbon price is not considered.

[b]Average carbon price from April 2010 to March 2011: £12.69/t CO2 [203]

8.3.2 Environmental data and assumptions

The indicators used for the environmental assessment are shown in Table 2. The key assumptions and data sources are summarised below.

8.3.2.1 Material recyclability

Recyclability of input materials

Material recyclability is the percentage of materials used for manufacturing and installation of a solar PV system that can potentially be recycled. In this case, all materials have a potential recyclability of 100% apart from glass-fibre reinforced plastic (GFRP). Like concrete, GFRP can only be downcycled rather than recycled: this is achieved by grinding the GFRP into sand, which can then replace the aggregate normally added to cement to produce concrete. In the Ecoinvent v2.2 database [204] concrete contains 1890 kg of aggregate per 2380 kg concrete, meaning downcycled GFRP sand potentially constitutes 79.4% of concrete (= 1890 ÷ 2380). Therefore a value of 79.4% is used to represent the downcycling of GFRP.

Recyclability is calculated based on the amounts of materials used for a CdTe (cadmium telluride) residential system with a slanted, roof-mounted installation in the Ecoinvent database [204]. The recyclability of such a system is illustrated in Table 35. The material requirements in Ecoinvent describe one square metre of PV panels with an equivalent capacity of 69.44 Wp. These data have been normalised to 1 kWp capacity and therefore represent the material requirements of 14.4 m^2 of panels (= 1 m^2 × (1000 Wp ÷ 69.44 Wp)).

Table 35: Major materials used for manufacture and installation of solar PV and their end-of-life recyclability for a residential CdTe system including panels, inverter and roof mounting, normalised to 1 kWp capacity [204]

Material	Amount (kg)	Recyclability (%)
Low-alloyed steel	27.33	100
Copper	11.87	100
Aluminium	65.32	100
Nickel	0.26	100
Tin	0.26	100
Ethylvinylacetate	9.07	100
High-density polyethylene and other plastics	0.41	100
Glass-fibre reinforced plastic	0.58	79.4
Solar glass	304.00	100
Corrugated board	23.46	100
Minor materials	1.07	not assessed
Total materials	*443.6*	
Total recyclability of the plant		**99.7% (442.4 kg)**

Solar PV technologies are quite diverse. CdTe is a technology that has increased in popularity in recent years due to low costs, but does not represent the majority of installed capacity (see [335]). To encompass a greater range of technologies, the results shown in Table 35 were validated by repeating the same process for a multi-Si laminate installation, normalised to an identical capacity of 1 kWp (in this case representing 11.59 m^2 of panels). This resulted in a very similar recyclability potential of 99.3%. Due to this good agreement, the original value of 99.7% was retained as the central estimate. The lower bound of the estimate (23.8%) corresponds to the amount of material that would be recycled at current UK demolition rates (see Section 4.3.2.2, Table 9). The large difference is due to the current lack of glass recycling in the construction industry [214].

8.3.2.2 Other environmental issues

Environmental (LCA) impacts

Data for solar PV have been adapted from models in the Ecoinvent v2.2 database [204] as follows:

- due to a lack of UK-specific data, an average world mix of PV technologies has been assumed [335] comprising 38.5% mono-crystalline Si panels and laminates, 52.3% multi-crystalline Si panels and laminates, 4.7% amorphous Si panels and laminates, 2.9% ribbon

Si panels and laminates and 1.6% CdTe and CIGS (cadmium-indium-gallium-selenide) panels;

- as mentioned in the assumptions section, PV outputs have been adjusted to UK insolation, according to data from IEA-PVPS [336] and Munzinger et al. [329], assuming 750 kWh/kWp/year.

The individual technologies listed above illustrate the diversity of solar PV as a technology group. For this reason, sensitivity analysis addresses as broad a range of technologies as possible, as follows:

- each technology mentioned above has been modelled on a slanted roof installation under UK insolation of 750 kWh/kWp/year;
- mono- and multi-crystalline Si panels and laminates have additionally been modelled on building façade installations, and the panel versions have also been modelled for a flat roof mounting; and
- the effect of end-of-life recycling of all major components has been explored using current UK demolition recycling rates, as described in Table 9 (see Section 4.3.2.2), applied to a mono-Si panel installation mounted on a slanted roof. This contrasts with the assumption used in the central estimate in which end-of-life recycling is not considered.

<u>Greenfield land use</u>

The indicator addresses only the operational stage, during which residential solar PV systems do not occupy land that would otherwise be free for alternative purposes (they occupy only rooftops).

8.3.3 Social data and assumptions

The indicators used for the social assessment are shown in Table 2. The data sources used are discussed below.

8.3.3.1 Provision of employment

<u>Direct and total (including indirect) employment</u>

Wherever applicable the same data sources have been used for solar PV as for the other technologies considered in this work. Therefore, employment related to the extraction of ores and aggregates (for manufacture of concrete, steel and other metals) has been calculated based on material requirements specified in Ecoinvent [204] and employment data from BHP Billiton [216] and the Mineral Products Association [217]. The processing of raw materials into metals is based on labour data from Corus [218].

Employment owing to the manufacture of PV panels has been estimated for mono- and multi-Si as well as CdTe thin film. The estimates have then been averaged. Mono- and multi-Si figures are based on the production workforce and annual output of Sharp's European manufacturing plant in Wales [337]. CdTe figures are based on data from First Solar's panel manufacturing plants in Germany and Arizona [338, 339]. These sources have been selected as they provide a complete, recent dataset and address several technology types (mono-Si, multi-Si and CdTe). Additionally, the Sharp plant is a major supplier to the UK market. The labour intensity of the three plants was found to be quite uniform, with each plant falling within 10% of the average. Data are not available on the number of workers required to install a residential PV system, therefore results for the installation stage have been calculated on the assumption that three people work full time for 2.5 days. This time period is derived from the estimate of 2-3 days given by Southern Solar [327].

Results for operation and maintenance have been derived from employment and installed capacity figures reported by the Federal Environment Ministry of Germany, averaged from 2007-2010 [340-343]. These data represent a comprehensive dataset; no equivalent data are available for the UK. Germany has a well developed solar PV market and thus should provide a good indication of O&M requirements. However, the only figures available include employment due to manufacture of replacement parts, which has not been included in the assessment of other technologies considered in this research. Therefore, for consistency, the German employment figures have been modified with a factor of 0.25 following discussion with the lead author of the Ministry's reports [344] in order to exclude indirect O&M employment. This is an approximation derived from unreleased data and the author's understanding of the PV sector; the results are therefore tentative.

Due to a lack of data, and in agreement with the cost estimates discussed in Section 8.3.1.4, the decommissioning stage has been allocated to roof replacement and therefore assumed to be zero on the basis that solar panels are likely to be removed only when roof replacement is necessary.

The above stages together form the total employment estimate. Direct employment is that resulting only from the installation and operation stages.

8.3.3.2 Human health impacts

Worker injuries

Worker injury results are calculated from the number of person-years of employment for each life cycle stage using Health and Safety Executive data [151] appropriate for the respective type of labour, as shown in Table 36.

Table 36: Injury rates used to calculate worker injuries in the solar PV life cycle [151]

Life cycle stage	HSE sector-specific injury rate used	Number of injuries per 100,000 workers
Manufacture of PV panels		
Extraction of ores/aggregates	Other mining	859.6
Processing	Manufacturing (total)	811.8
Manufacture of components	Manufacturing (total)	811.8
Installation	Construction (total)	777.2
Operation	Electricity, gas, steam and hot water supply (total)	553.8

Human toxicity potential & Human health impacts from radiation

These two impacts are estimated as part of LCA (see Section 8.3.2.2).

8.3.3.3 Large accident risk

Fatalities due to large accidents

Data from the Paul Scherrer Institut [221] provide an estimate of large accident fatalities, drawing on their Energy-Related Severe Accident Database (ENSAD) [222, 223]. As in the ENSAD, large accidents are defined as those causing at least five fatalities. These results represent present-day Swiss conditions, but are likely to be appropriate for the UK as production processes and installation techniques are common to both countries.

8.3.3.4 Local community impacts & Human rights and corruption

These impacts have not been considered, as they are company-specific and therefore cannot be assessed at the generic technology level.

8.3.3.5 Energy security

Avoidance of fossil fuel imports & Fuel supply diversity

As described in Section 3.2.3.6, the amount of imported fossil fuel potentially avoided is calculated from the average efficiency of the current UK fossil fuel fleet [calculated from 16] on the basis that a unit of electricity generated by non-fossil capacity displaces a unit generated by fossil capacity.

As solar power is fuel-free, it is not subject to fuel supply disruption and has therefore been assigned the maximum score of 100 in the diversity of fuel supply indicator.

Fuel storage capabilities

As is the case with wind power (see Section 7.3.3.5), solar PV has zero fuel storage capabilities because, despite sunlight having a derivable energy density, it cannot be stored. The electricity produced by a solar PV system could be stored, for example in batteries or via pumped storage, but this applies equally to all forms of electricity production and is not an attribute of solar PV.

8.3.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

This indicator is not applicable to the solar power life cycle (for further description see Section 3.2.3.7), so it is assigned a score of zero.

8.3.3.7 Intergenerational equity

Abiotic resources (elements and fossil fuels)

These indicators have been estimated as part of LCA (see Section 8.3.2.2).

Volume of radioactive waste and liquid CO_2 for storage

This indicator is not applicable to the solar power life cycle (for further description see Section 3.2.3.8). Solar PV is assigned a score of zero.

8.4 Results and discussion

This section presents the assessment results for the solar PV option. The summary results are shown in Figure 28, Figure 29 and Figure 30; full results can be found in Appendix 3.

8.4.1 Techno-economic sustainability

This sub-section addresses the techno-economic part of the sustainability assessment of solar PV. The results are presented in Figure 28 and discussed below.

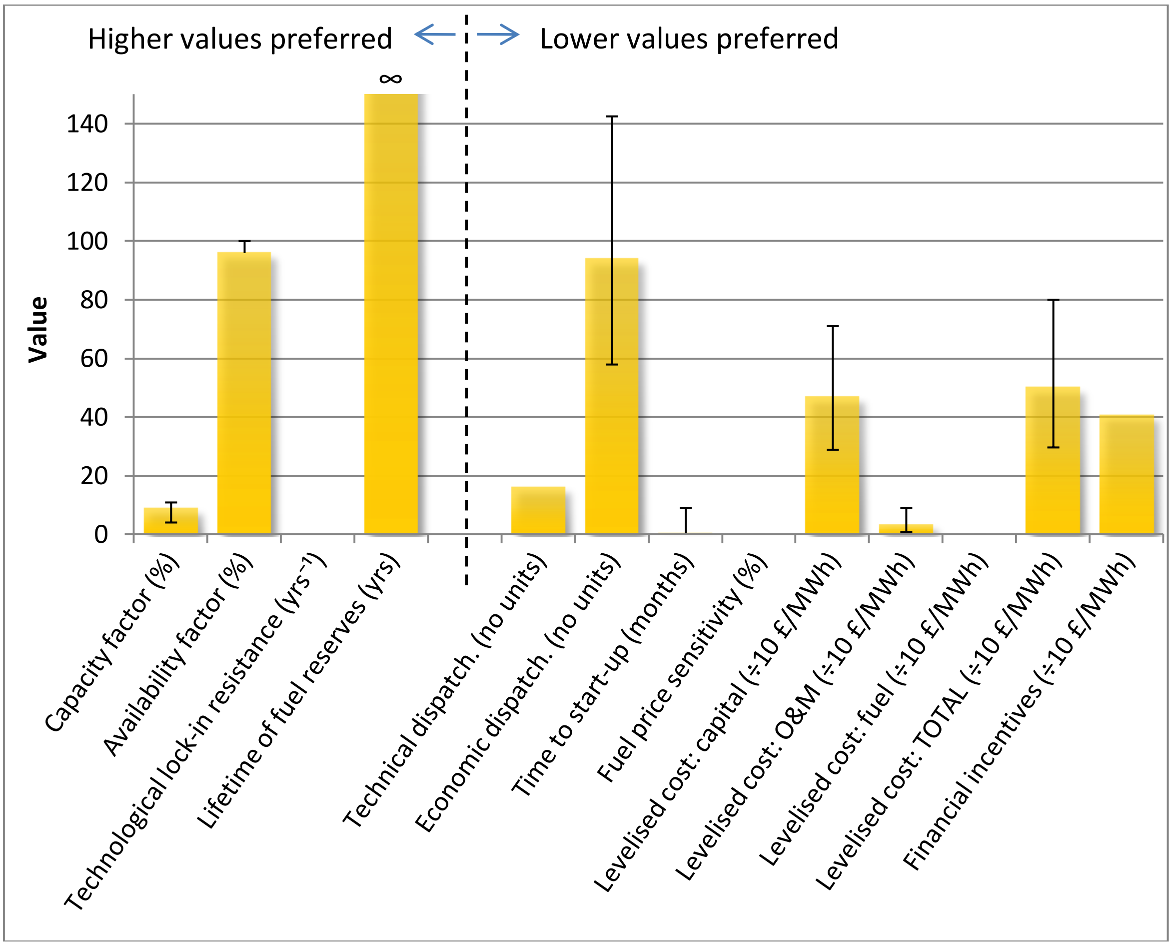


Figure 28: Techno-economic sustainability of solar PV. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases apart from *availability factor*, for which a current average is used. The *lifetime of fuel reserves* for solar power is effectively infinite. For full results, see Appendix 3**.**

8.4.1.1 Operability

Capacity and availability factors

As shown in Figure 28, there is a large difference between the capacity factors and availability factors of solar installations (8.6% and 96%, respectively), reflecting the fact that their output is constrained far more by incident sunlight than by reliability. Geographical location and orientation are therefore the main determinants of capacity factor: for instance, a horizontally mounted panel in Scandinavia may have a capacity factor as low as 5.4% (470 kWh/kWp/yr), whereas an optimally oriented panel in Portugal can achieve over 17% (1510 kWh/kWp/yr) [330]. However, shading of panels and reliability of inverters have also been highlighted as significant causes of reduced output [329], potentially giving capacity factors of 4% (the lower bound). As discussed in Section 8.3.1.1, a typical residential PV system in the UK is expected to have a capacity factor of around 8.6% while total lack of shading and a southern location can increase this figure to around 10.8% (the upper bound). Availability of solar PV is generally very high (96-100%) as might be expected for a system without moving parts.

Technical and economic dispatchability

Solar power is inherently non-dispatchable as output cannot be controlled, and it accordingly has the worst possible score for technical dispatchability (16). Moreover, even if it were technically dispatchable it would not be economic to load-follow do so due to the fact that 94% of total levelised cost is capital: after such a significant initial investment, it is not financially practical to reduce output because payback time would increase significantly. Indeed, within the range of costs considered (see Section 8.3.1.4), the capital cost of certain installations can be higher than the total levelised cost of others, meaning the value for economic dispatchability can exceed 100% (total range: 58-143%).

As is the case for wind power (see Section 7.4.1.1), this lack of dispatchability poses problems in terms of grid management: the greater the proportion of national electricity supplied by variable sources, the more difficult it becomes to match supply to demand without resorting to expensive energy storage and/or back-up capacity. However, daily electricity demand typically increases and decreases in correlation with working hours, which also approximately match solar irradiance and therefore PV output. As a result, lack of dispatchability is expected to be less problematic for solar PV than for wind power. Given the relatively tiny contribution of solar power to the current UK electricity mix (0.005% in 2009 [16]), expansion can likely continue for decades without causing significant grid management problems. However, the point at which problems might arise is currently unknown and depends on, amongst other factors, uptake of demand-side management technologies (i.e. smart grid features) and penetration of wind power (see Section 7.4.1.1).

Lifetime of global fuel reserves

Solar PV is a fuel-free technology; its 'fuel reserves' are equivalent to the remaining life of the Sun, so are infinite in practical terms.

8.4.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

Solar PV cannot provide trigeneration, negative global warming potential or thermochemical hydrogen production, and therefore scores zero for this indicator. It is possible to use solar-generated electricity to produce hydrogen by hydrolysis, but this is equally applicable to all electricity generating technologies.

8.4.1.3 Immediacy

Time to start up

Solar power performs very well in this respect, with installation normally completed in 2-3 days (central estimate = 0.1 months). However, this partly reflects the small size of PV installations in comparison to other technologies (circa 3 kW compared to >100 MW for most other options). A more direct comparison may be found in larger photovoltaic installations, such as the 70 MW Rovigo plant which was completed in nine months [345]: this still compares favourably to the similar-sized 90 MW Barrow and Burbo Bank wind farms (11 and 15 months, respectively; see Section 7.4.1.3).

8.4.1.4 Levelised cost of generation

Capital, operational, fuel and total costs

The costs shown in Figure 28 exclude incentives provided by market mechanisms, which are discussed in Section 8.4.1.6. They are not, therefore, the net costs paid by owners. At 10% discount rate, the solar PV option costs 29.6-80.0 pence/kWh with a central estimate of 49.8 pence/kWh, which is 7.6 times the cost of natural gas power and 3.4 times that of offshore wind.

Of this total cost, 94% is the initial capital expenditure, with maintenance comprising the remaining 6%. The lack of fuel costs means the total cost of electricity from a solar PV installation is set from the outset (aside from unforeseen maintenance costs). This contrasts strongly with gas, where 75% of the cost is due to fuel and less than 20% due to the power plant itself [99], meaning production costs are highly volatile over time. Similarly to nuclear and offshore wind power, the large capital component of solar PV does, however, increase risks if future revenue is in any way uncertain. This was highlighted recently when the UK Government reduced the Feed-in Tariff (FiT) by approximately 50% [326], meaning projects that had already been arranged but had not progressed to the point of registering for the tariff suddenly became far less profitable.

8.4.1.5 Cost variability

Fuel price sensitivity

As discussed above, solar PV is fuel-free and thus has no fuel price sensitivity. This decreases exposure to the risks posed by volatile fuel prices which are a significant problem for fossil-based power, particularly gas power (see Section 5.4.1.5).

8.4.1.6 Financial incentives

Financial incentives and assistance

The quantification and results of this indicator are discussed in Section 8.3.1.6 (see Table 34). From this, it is clear that the main incentive for prospective solar PV owners is the Feed-in Tariff (FiT), which at the time of writing awards 43.3 pence/kWh for a residential, retrofitted installation (or 37.8 pence/kWh for new build). Once the avoided carbon tax has also been included, this brings the total incentive to 40.55 pence/kWh. This is far higher than the subsidies available to any other technology: offshore wind, for example, receives 8.2 pence/kWh (Section 7.4.1.6). According to the lower estimate of PV costs discussed above, this incentive may amount to 137% of the cost of solar PV, providing a significant profit without even selling any electricity back to the grid[33]. In the case of large-scale PV installations (>50 kWp), which tend to be cheaper, the FiT subsidy is up to 19 p/kWh (depending on size). With an expected cost of 28.2 p/kWh [333], large installations are therefore subsidised by up to 67% on top of any revenue from electricity sales. As the UK Government believes these incentives are too high, it has recently cut payments approximately in half [see 346] for new installations, reducing the FiT for residential PV to 21 p/kWh and, for larger systems, up to 12.9 p/kWh (depending on size). However, even under this new system, residential PV will receive a subsidy several times greater than any other

[33] FiT payments are based on the total amount of electricity generated, regardless of how much is exported to the grid.

technology. Moreover, owners who registered before 3rd March 2012 will receive the old, higher FiT rates for the 25 year life of the agreement.

Eventually this system will be replaced by the recently announced 'contract-for-difference'[34] which will directly subsidise producers of low-carbon electricity by guaranteeing them a set sale price [28]. However, this is not included here as its potential impact is currently unclear.

8.4.2 Environmental sustainability

This sub-section addresses the environmental assessment of solar photovoltaics. All environmental indicators, except for material recyclability and greenfield land use, have been estimated using life cycle assessment (LCA) and the CML 2001 impact assessment methodology (the November 2009 update) [59, 139]. GaBi v4.4 LCA software [244] and the Ecoinvent v2.2 database [204] have been used for these purposes. All estimates are based on modelling undertaken in this study.

The results are presented in Figure 29 and discussed below.

[34] The 'contract-for-difference' mechanism is essentially a long-term sale price guarantee, with the caveat that any revenue exceeding the set price (or 'strike price') is paid back to the government. For instance, a generator with an agreed strike price of 7 p/kWh is guaranteed that income – if the electricity is sold for 4 p/kWh, the government pays the generator the remaining 3 p/kWh – but if the generator sells for 8 p/kWh, the extra 1 p/kWh is paid back to the government [28].

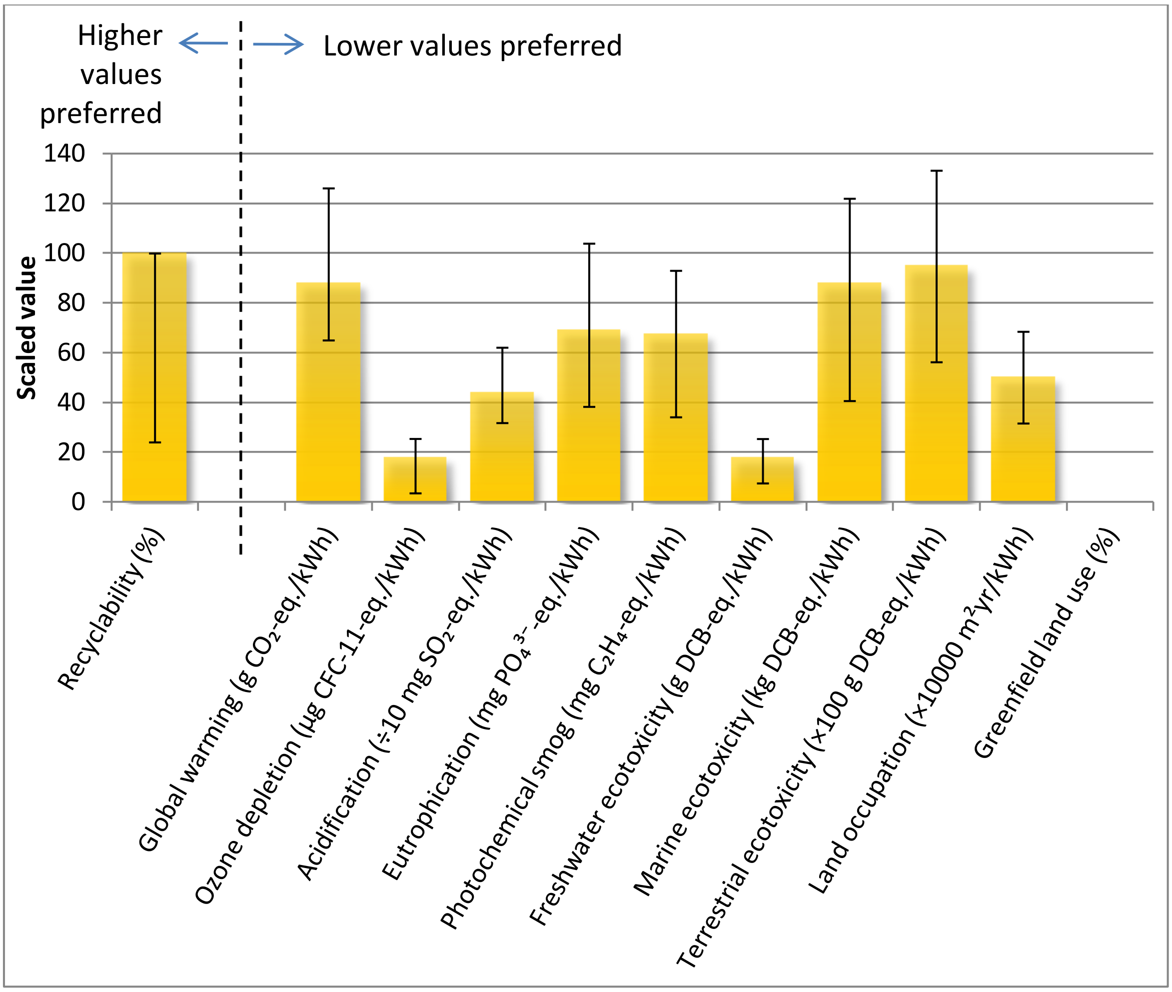


Figure 29: Environmental sustainability of solar PV. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled by multiplying or dividing their original values by the factors shown in brackets. Bar height represents the central estimate in all cases. For full results, see Appendix 3.

8.4.2.1 Material recyclability

Recyclability of input materials

Figure 29 (and Table 35 in Section 8.3.2.1) shows that the potential recycling rate of a residential PV installation is very high at around 99.7%. However, the bulk of the mass of a typical solar panel is glass, and virtually no flat glass is currently recycled in the UK construction sector [214] resulting in the very low overall recyclability estimate given as a lower bound (23.8%). Due to the complexity of solar panels, it is likely that maximum recycling rates will only be reached by targeted solar recycling programmes (as opposed to normal construction-sector practices).

Table 37 uses results from the sensitivity analysis to illustrate the potential reductions in environmental impact that can be achieved by recycling the components of a residential solar PV system at current UK rates (given in Table 9 in Section 4.3.2.2). This shows that, despite the current lack of flat glass recycling in the UK, significant improvements can be brought about by recycling the other components. This contrasts greatly with end-of-life recycling of conventional plants such as coal, gas and nuclear, which offers limited benefit (see Table 13, Table 20 and Table 27). This is because the vast majority of environmental burdens created by the solar PV life cycle occur during the manufacture of components (see Appendix 3 for full results by life cycle stage). Clearly as PV recycling rates increase, potentially including recycling of glass, the reduction in PV life cycle impacts will improve markedly.

Table 37: Percentage reduction in impacts due to recycling of solar PV installation components at end-of-life, using current UK recycling rates

Impact	Reduction of impact at current UK recycling rates[a] relative to no recycling (%)
Global warming potential	16.54
Ozone depletion potential	4.29
Acidification potential	24.37
Eutrophication potential	13.28
Photochemical smog potential	15.47
Freshwater eco-toxicity potential	51.95
Marine eco-toxicity potential	49.22
Terrestrial eco-toxicity potential	36.72

[a] Aluminium 95%, other metals 99%, plastics 26%, concrete 71.5%, fibre cement facing tile 0%, paper 69%, gravel 30%, glass fibre reinforced plastic 10%, ceramic tiles 64%, insulation 18%, glass 0% (see Section 4.3.2.2).

8.4.2.2 Global warming potential (GWP)

Figure 29 shows a range of GWP estimates for solar PV of 64.8-125.9 g CO_2 eq./kWh with a central estimate of 87.8 g. This is similar to other present-day estimates for residential solar PV in literature: for example, 62 g CO_2 eq./kWh (PSI [246]); 20-170 g CO_2 eq./kWh (POST [293]); and 16-49 g CO_2 eq./kWh (Fthenakis and Kim [347]). The results in this study are slightly higher than some due to the lower insolation in the UK (see Section 8.4.1.1).

The GWP of solar PV is higher than that of nuclear of offshore wind power (6.2 and 11.2 g CO_2 eq./kWh, respectively), but less than a quarter of the GWP of gas power (379 g). For reference, the current average GWP from the UK electricity mix is 584 g CO_2 eq./kWh [204]. Carbon dioxide accounts for 86% of solar power's GWP, with the manufacture of the panels themselves causing around 75% of the total impact. The inverter and mounting system account for about 7.5% and 13%, respectively.

8.4.2.3 Ozone layer depletion potential (ODP)

Residential solar PV has an ODP of 17.5 μg CFC-11 eq./kWh in the central case, with a range of 3.3-25.2 μg depending on the specific PV technology used (see Appendix 3 for full results). This is a relatively high value, almost 40% higher than the value for natural gas and around 30 times the impact of either nuclear or offshore wind power (0.54 and 0.60 μg CFC-11 eq./kWh, respectively). The production of the panels accounts for over 90% of this impact, the reason being the manufacture of tetrafluoroethylene, the polymer of which, Teflon, is often used in solar cell encapsulation. As shown in Appendix 3, the ODP of solar power is considerably lower if more advanced technologies are used, such as amorphous-Si laminate, CdTe or CIGS. Even in these cases, however, the impact is an order of magnitude higher than that of nuclear or offshore wind.

8.4.2.4 Acidification potential (AP)

Life cycle AP of is estimated at 0.44 g SO_2 eq./kWh within a range of 0.32-0.62 g. In this respect solar PV is around four times better than coal power (the exact improvement depending on the amount of pollution abatement technology assumed in the coal plants (see Section 6.4.2.4)). However, natural gas, offshore wind and nuclear power are all preferable to solar PV in terms of their AP. SO_2 and NO_x account for around 97% of this impact, being emitted throughout the life cycle primarily during metal production chains.

8.4.2.5 Eutrophication potential (EP)

The estimate of EP for solar power is 0.038-0.10 g PO_4^{3-} eq./kWh with a central estimate of 0.069 g. This is comparable to the offshore wind and gas power life cycles which emit 0.060 and 0.062 g, respectively. Most of this impact (75%) occurs during manufacture of the solar panels themselves, but production of the inverter and roof mounting system are also significant contributors (10% and 9%, respectively). More advanced technologies have lower eutrophication potentials of which the best option is amorphous-Si laminate with a value of 0.038 g PO_4^{3-} eq./kWh.

8.4.2.6 Photochemical oxidant creation potential (POCP)

The POCP of the solar PV life cycle is 0.067 g C_2H_4 eq./kWh, which is intermediate between the impacts of coal and natural gas power. Nuclear and offshore wind power are around 13.5 and 8 times better in terms of POCP, respectively. Over 50% of this impact is due to emission of non-methane volatile organic compounds, particularly during the manufacture of PV cells from Si wafer. It is for this reason that the maximum estimate for PV (0.093 g C_2H_4 eq./kWh) corresponds to a façade-mounted single-Si system, while the lower impacts are associated with non-Si technology, the lowest being 0.034 g achieved by a slanted roof-mounted CIGS system.

8.4.2.7 Water eco-toxicity

Freshwater eco-toxicity potential (FAETP)

The central estimate of FAETP is 17.4 g DCB eq./kWh (within a range of 7.3-25.2 g), which is comparable to that of coal power (16.7 g) and slightly lower than that of nuclear (21.1 g) and offshore wind (21.4 g) although the ranges overlap considerably. The production chains of metals such as copper and steel are the main causes, primarily via emissions of metals such as vanadium, nickel and copper to freshwater, which together account for around 84% of the impact. Because the FAETP in the solar power life cycle is so strongly correlated with metal use, the minimum impact (7.3 g DCB eq./kWh) is achieved by recycling components to negate some of their production impacts.

Marine eco-toxicity potential (MAETP)

Solar PV has an MAETP of around 87.6 kg DCB eq./kWh, spanning a range of 40.4-121.7 kg. Despite being several times lower than the equivalent value for coal power (578 kg DCB eq./kWh), this is approximately double the impact attributable to nuclear or offshore wind power and 12 times that of natural gas. Approximately 75% of this impact is due to the emission of hydrogen fluoride to air, mainly due to the use of hydrofluoric acid to remove impurities during the manufacture of metals and silicon.

8.4.2.8 Land use and quality

Terrestrial eco-toxicity potential (TETP)

TETP for the PV life cycle is estimate at 0.94 g DCB eq./kWh with a possible range of 0.56-1.33 g, as shown in Figure 29. This is comparable to the impact of nuclear power (0.74 g) and appreciably lower than that of offshore wind (1.43 g) or coal power (1.53 g) although the single-Si façade-mounted installations at the top of the estimated range approach those values due to their low electrical output. Emission of chromium to air and industrial soil causes 51% of this impact, primarily resulting from stainless steel production, while most of the remainder is due to emission of other heavy metals to air such as arsenic and mercury.

Land occupation

The solar PV life cycle requires 0.0031-0.0068 m^2yr/kWh with a central estimate of 0.0050. This is relatively high considering the fact that the solar panels themselves account for none of this area due to rooftops being excluded from the estimate. The land occupation of offshore wind power, for instance, is an order of magnitude lower at 0.0004 m^2yr/kWh. The high material requirements of solar systems, particularly for metals, together with their relatively low electrical output in countries with low insolation mean that large areas are required for extraction and manufacturing per unit of electricity produced.

Greenfield land use

As discussed in Section 8.3.2.2, greenfield land use only considers the operational stage of the life cycle, at which point residential solar power occupies no land. Greenfield land use is therefore zero.

8.4.3 Social sustainability

This sub-section addresses the social part of the sustainability assessment of residential solar PV. The results are presented in Figure 30 and discussed below.

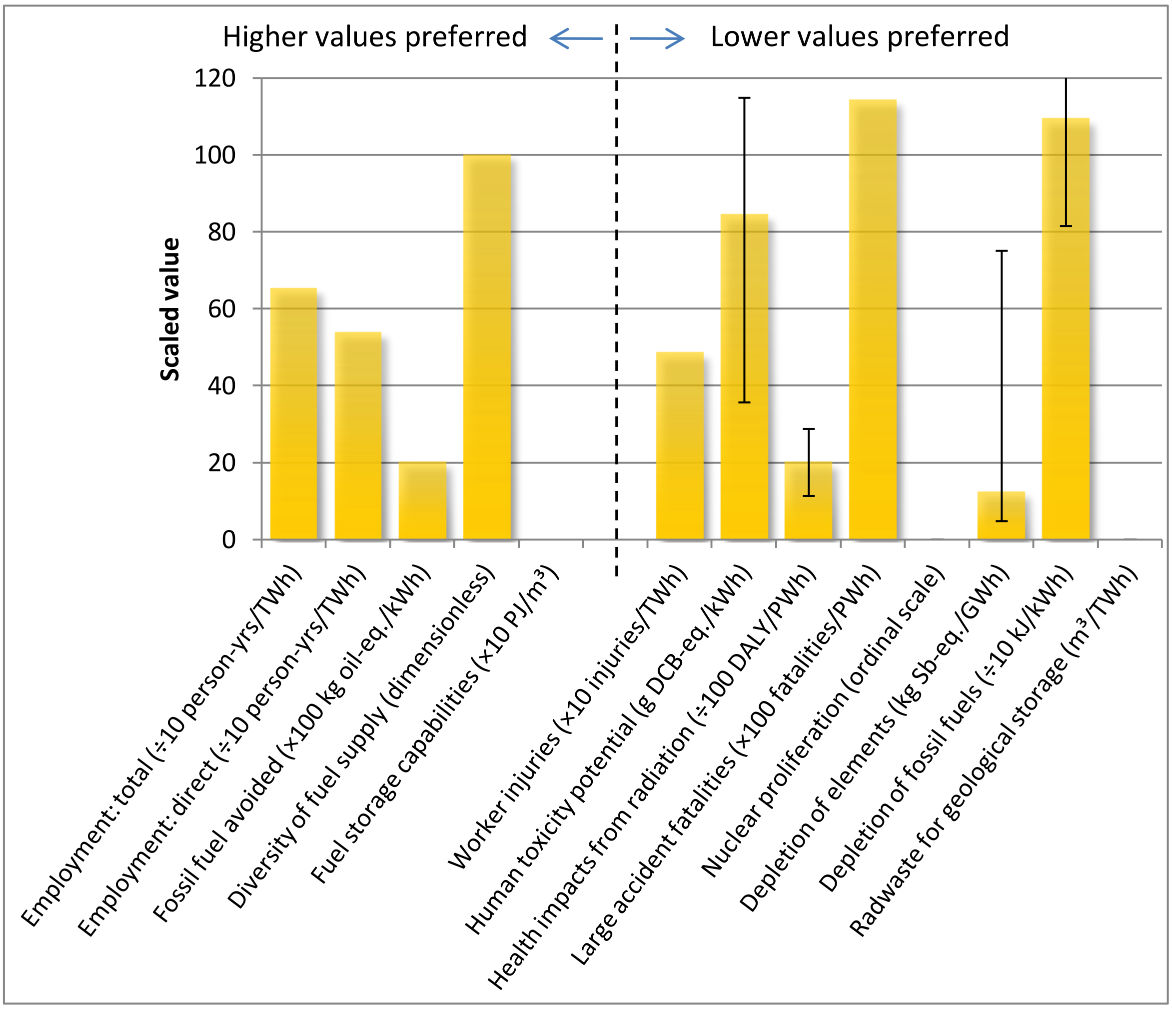


Figure 30: Social sustainability of solar PV. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases. The upper value of the estimate for *depletion of fossil fuels* is 1.58 MJ/kWh (158 on the graph's scaled *y* axis). For full results, see Appendix 3**.**

8.4.3.1 Provision of employment

<u>Total employment</u>

Both direct and indirect employment are shown in Figure 30. The former is related to the PV system's installation, operation and maintenance while the latter refers to jobs in the raw material extraction and manufacturing stages of the life cycle. Residential solar PV is estimated to provide 653 person-years/TWh of employment. This is around 80% more employment than is generated by the offshore wind life cycle and ten times that generated by gas power.

The reason that PV achieves such high employment figures is in part due to its low capacity factor (around 8.6%; see Section 8.4.1.1): electrical output is relatively low compared to the fixed labour requirements for manufacturing, installation and maintenance, meaning that employment per unit of electricity generated is high. In sunnier countries, electrical output may be twice as high as in the UK, meaning employment per terawatt-hour would be much lower.

Approximately 63% of domestic PV employment is due to the installation of the system and an additional 19% is due to maintenance. However, as discussed in Section 8.3.3.1, employment during maintenance has to be estimated by modifying German figures to exclude the manufacture of replacement parts. If this extra manufacturing and other indirect operational activities are included, the employment for PV increases significantly to 1022 person-years/TWh.

Direct employment

If indirect employment is excluded from the total, domestic PV provides 537 person-years/TWh, 77% of which is due to installation of the panels.

8.4.3.2 Human health impacts

Worker injuries

As shown in Figure 30, the solar PV life cycle causes around 4.8 injuries/TWh. Two thirds of these are expected to occur in the installation stage. This rate of injury is very high, exceeding that of the coal life cycle (4.5 injuries/TWh); this is mainly a consequence of solar power's high employment provision.

Human toxicity potential (HTP), excluding radiation

Solar PV has a relatively high HTP with a central estimate of 84.4 g DCB eq./kWh, primarily due to aerial emissions of arsenic, nickel, chromium and cadmium. This result is comparable to offshore wind and coal power (73.6 and 77.7 g, respectively), but an order of magnitude higher than the gas power result (5.4 g). However, while 78% of HTP from coal power is caused in the operational stage by coal combustion, the impact from PV is predominantly accrued during metal production chains and can therefore be reduced by recycling: the sensitivity analysis shows that recycling a mono-Si PV panel at current UK rates reduces its HTP by 54% to 35.7 g DCB eq./kWh (see Appendix 3), at which point it is superior to offshore wind and coal power. Conversely, PV system with lower capacity factors, such as those mounted on building façades, can have an HTP as high as 115 g DCB eq./kWh due to lower output.

Total human health impacts from radiation

The PV life cycle causes 1.99 disability-adjusted life years (DALYs) per TWh due to radiation with a range of 1.13-2.88 (Figure 30). This impact is worse than that of offshore wind, natural gas or coal but remains ten times lower than the impact attributable to nuclear power (20.3 DALYs/TWh).

8.4.3.3 Large accident risk

Fatalities due to large accidents

As shown in Figure 30, based on historical accidents, the Paul Scherrer Institut estimate that solar PV causes 1.14 fatalities/PWh [221]. This makes solar PV broadly comparable to offshore wind power in this respect (0.77 fatalities/PWh), and equates to 18 times fewer fatalities than those caused by coal power. Like wind power, individual accidents in the PV life cycle are extremely unlikely to cause more than 10 deaths (as opposed to the 49,000 potential fatalities caused by a nuclear accident) which greatly reduces the perceived danger of solar PV.

8.4.3.4 Local community impacts and human rights & corruption

As mentioned in Section 8.3.3.4, these impacts have not been considered because they are company-specific and therefore not applicable for technology assessment. For further discussion, see Section 3.2.3.

8.4.3.5 Energy security

Avoidance of fossil fuel imports

As described in Section 3.2.3.6, approximately 200 tonnes of oil-equivalent (toe) per GWh is used by the UK's current fossil-fuel power stations on average. Non-fossil capacity such as solar PV therefore increases resilience to fossil fuel price volatility. However, given that solar power is non-dispatchable and variable in its output, an increase in solar capacity will force the remaining fossil plants to follow load more actively, in turn reducing their efficiency. Consequently, the figure of 200 toe/GWh is probably an overestimate of the fuel avoided by PV.

Diversity of fuel supply mix

As solar power is fuel-free, it is not subject to fuel supply disruption and has therefore been assigned the maximum score of 100 for the diversity of fuel supply indicator.

Fuel storage capabilities

Sunlight cannot be stored so solar PV has a score of zero for this indicator. As noted in Section 8.3.3.5, the electricity produced by a PV system could be stored, in batteries for example, but this is not an attribute of solar PV: the same applies to any other electricity generation technology.

8.4.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

This indicator is not applicable to solar PV, which has therefore been assigned a score of zero.

8.4.3.7 Intergenerational equity

Use of abiotic resources (elements)

The use of elemental resources in the solar PV life cycle is 4.8-75.1 kg Sb eq./GWh with a central estimate of 12.3 kg. The high upper estimate of 75.1 kg Sb eq./GWh is due to the inclusion of CdTe technology in the range of models assessed: a 3 kWp CdTe installation requires around 28.5 kg of cadmium and 9.1 g of tellurium, which is extremely rare; the cadmium requirement alone accounts for 88% of the impact.

Even in more common technologies, such as multi-Si panels (which require 10.8 kg Sb eq./GWh), the impact is 13 times greater than that of offshore wind and 230 times that of the nuclear life cycle. In this case, the majority (91%) of the impact is due to the use of tellurium, silver and gold, primarily for metallisation of silicon solar cells.

Use of abiotic resources (fossil)

The life cycle of solar PV depletes 1.1 MJ/kWh, which is 8 and 13.5 times more than offshore wind or nuclear power, respectively, and represents a saving of only 81% over the gas power life cycle despite being a non-fossil fuel option. Most of this impact (around 75%) is attributable to the solar panels themselves, with a further 12% due to the roof mounting and 8% to the inverter. The reason fossil depletion is relatively high in the PV life cycle is its high metal requirements and subsequent fuel requirements in ore extraction and processing, as well as the high process heat needed for industrial processing and purification of silicon. As shown in Figure 30, the potential range of values is 0.82-1.6 MJ/kWh depending on the specific technology type.

Volume of radioactive waste and liquid CO_2 to be stored

Solar PV does not produce radioactive waste or liquid CO_2 for storage.

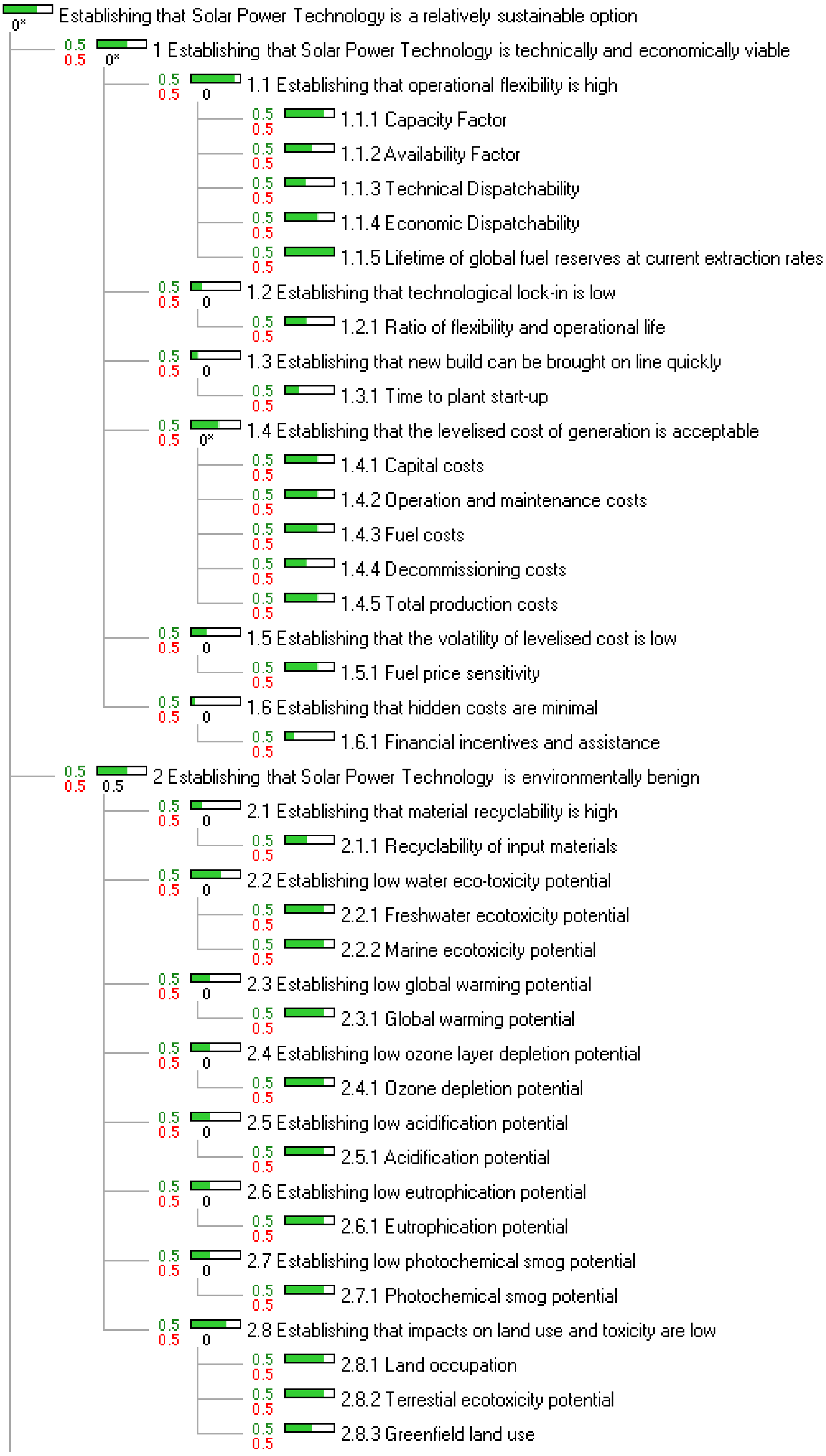
8.5 Data quality in the solar PV assessment

Data quality has been assessed using the same methodology as for the nuclear option and the other options assessed in this work (see Section 4.5 and Appendix 4).

Figure 31 summarises the data quality analysis. The overall assessment is rated at 69% (where a rating of 100% would indicate perfect quality). This is the same as the rating for offshore wind power and similar to that of natural gas (68%). The weakest of the three 'pillars' in this sustainability assessment is the environmental group, scoring 62.1%. The main reason for this is high dependency due to the LCA indicators sharing common data sources. Additionally the LCA modelling assumes a global average mix of PV technologies, as discussed in Section 8.3.2.2, which may not necessarily reflect the UK mix.

Overall, the data quality of the solar PV sustainability assessment is thought to be good given the purpose of this study: that is, a generic assessment of residential PV reflecting that currently being deployed in the UK. Improvements could be made by focusing on lower rated areas shown in Figure 31 as shorter green bars. Thus, the focal points of potential future work should include:

- improving the assessment of operability by including data on the availability of newer PV installations specifically in the UK and by incorporating more complex assessment of solar PV's dispatchability;
- improving financial incentives and assistance by extending the current data to include hidden subsidies as discussed in Section 3.2.1.6;
- further specifying the mix of PV technologies to the UK in the LCA modelling; and
- improving the employment estimate by using figures specific to the UK during the operational stage rather than adapting German data with an estimated correction factor to exclude employment from the manufacture of replacement parts (as discussed in Section 8.3.3.1).


0* Establishing that Solar Power Technology is a relatively sustainable option
0.5 0.5 0* 1 Establishing that Solar Power Technology is technically and economically viable
0.5 0.5 0 1.1 Establishing that operational flexibility is high
0.5 0.5 1.1.1 Capacity Factor
0.5 0.5 1.1.2 Availability Factor
0.5 0.5 1.1.3 Technical Dispatchability
0.5 0.5 1.1.4 Economic Dispatchability
0.5 0.5 1.1.5 Lifetime of global fuel reserves at current extraction rates
0.5 0.5 0 1.2 Establishing that technological lock-in is low
0.5 0.5 1.2.1 Ratio of flexibility and operational life
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0.5 0.5 1.6.1 Financial incentives and assistance
0.5 0.5 0.5 2 Establishing that Solar Power Technology is environmentally benign
0.5 0.5 0 2.1 Establishing that material recyclability is high
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0.5 0.5 0 2.7 Establishing low photochemical smog potential
0.5 0.5 2.7.1 Photochemical smog potential
0.5 0.5 0 2.8 Establishing that impacts on land use and toxicity are low
0.5 0.5 2.8.1 Land occupation
0.5 0.5 2.8.2 Terrestial ecotoxicity potential
0.5 0.5 2.8.3 Greenfield land use

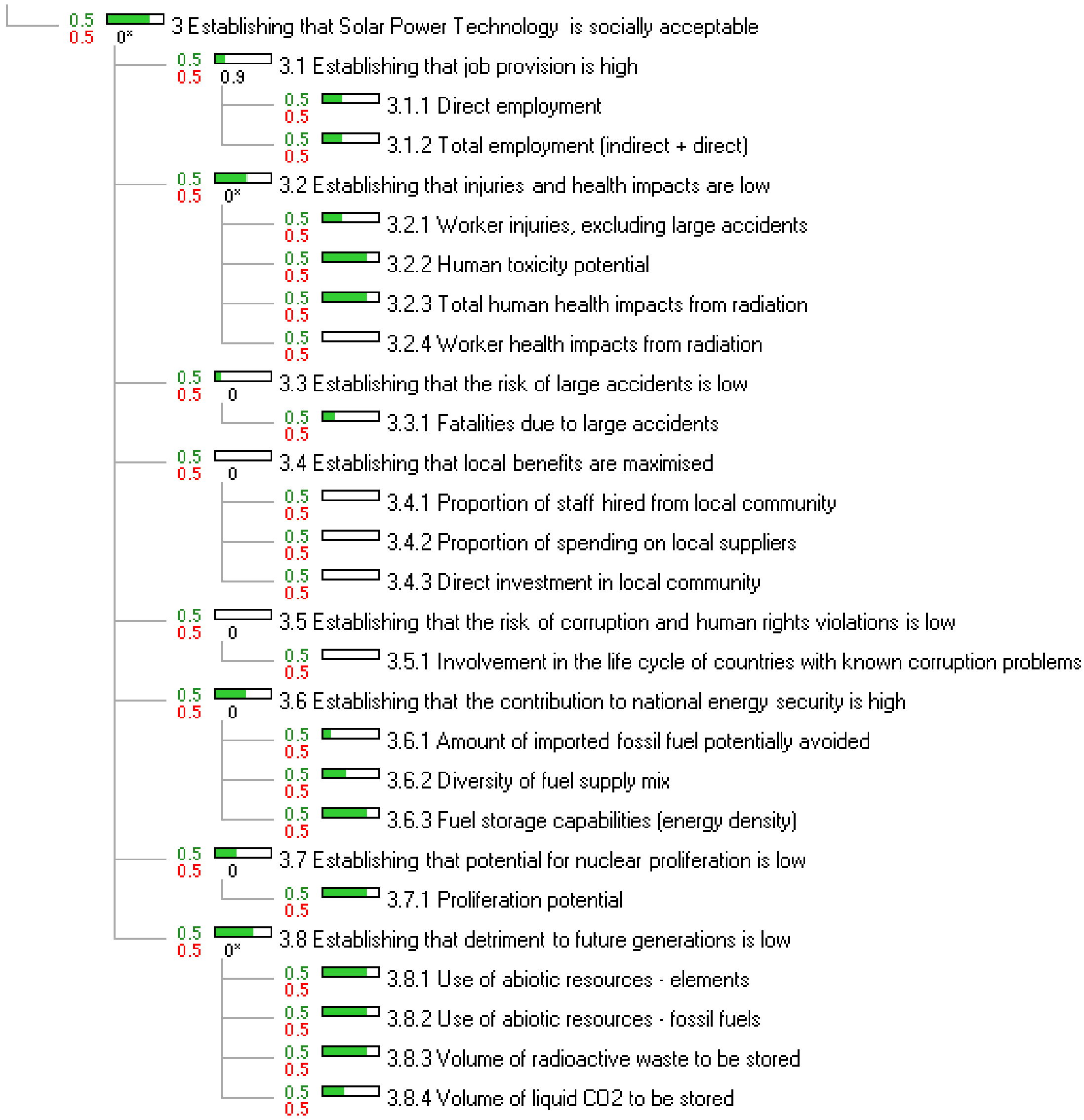

Figure 31: Data quality summary for the sustainability assessment of solar photovoltaics

8.6 Summary

The sustainability results for solar PV presented in this chapter can be summarised as follows:

- Like wind power, solar power is variable in output, therefore an electricity mix with a large solar contribution is inherently difficult to manage as it becomes harder to balance supply and demand. However, as solar output correlates roughly with electrical demand (high in the day, lower at night), this is less of a problem than might be the case for wind power. The capacity of solar PV at which variability becomes problematic is not currently known and will depend on the composition of the grid as a whole.
- The cost of domestic solar PV is currently high, estimated at 29.6 to 80.0 pence/kWh. As a result, the subsidies given to PV owners are also high, although they are currently being

reduced from 40.6 to 21 pence/kWh, at which level they will still be around 2.5 times as high as the subsidy received by offshore wind power. The cost of this subsidisation is ultimately borne by consumers.

- The main justifications for such a subsidy are zero carbon (at the operational stage) electricity and reduced fossil fuel imports. However, due to the relatively low insolation levels in the UK, capacity factors are expected to average around 9%, meaning that output from PV installations in the UK is approximately half what would be achieved in sunnier countries like Spain.
- The consequence of such a low capacity factor is increased material and energy requirements throughout the life cycle relative to electrical output. As a result, environmental performance is relatively poor: solar PV has high ozone layer depletion, acidification, eutrophication, photochemical smog, freshwater, marine and terrestrial eco-toxicity potentials. Global warming potential, at 88 g CO_2 eq./kWh, is several times higher than either nuclear or offshore wind power, but nevertheless around 4.5 times lower than natural gas power.
- Many of the environmental impacts can be improved significantly by recycling (on average by around 25%), as most impacts are accrued during resource extraction and processing. However, even then the impacts tend to be higher than other options such as nuclear, gas and, in several cases, offshore wind.
- One potential benefit of the high material requirement of the solar PV life cycle is that it provides high employment (although this is also accompanied by worker injuries).
- In terms of other social aspects, solar PV has relatively high human toxicity and abiotic resource (elements) depletion potentials, exceeding the impact of offshore wind by a factor of 15 in the latter case. In order to mitigate this, solar panels would need to be recycled at high rates.

Chapters 4-8 have presented sustainability assessments of electricity from nuclear power, natural gas, coal, offshore wind and solar photovoltaics using the methodology discussed in Chapter 3. The next chapter combines the results of all the above assessments in order to consider whole electricity mixes in the present and in the future.

9 Sustainability assessment of electricity mixes: the current situation and future scenarios

Following on from the sustainability assessment of individual technologies, this chapter illustrates how sustainability indicators can be applied to full electricity mixes based on those technologies. The aim of this is to explore the implications of potential future electricity scenarios in the UK and to assist with the planning and direction of future energy policy. Firstly, Section 9.1 explores the sustainability impacts of the current UK electricity mix by comparing directly the present-day technologies modelled and discussed in detail in Chapters 4-8. These findings are then used to assess the sustainability of the current UK electricity mix. Section 9.2 subsequently considers how the characteristics of technologies might change in the coming decades, before Section 9.3 describes how the sustainability indicators can be applied to a range of different electricity mixes out to 2070. Finally, Section 9.4 considers the results and implications of this scenario analysis as an input to the policy recommendations provided in the final chapter of this dissertation (Chapter 10).

9.1 Summary of present-day technologies and the UK electricity mix

The sustainability of nuclear, natural gas, coal, offshore wind power and solar photovoltaics has been discussed in Chapters 4-8, with results being compared where appropriate to provide context. However, the direct comparison is summarised below in Section 9.1.1. Section 9.1.1.4 then considers the implications of these results for an electricity mix approximating that of present-day UK conditions.

9.1.1 Comparison of present-day technologies

Figure 32, Figure 33 and Figure 34 compare the sustainability of all five assessed technologies. Results for each technology and its related sensitivity analyses can be found in Appendix 3.

9.1.1.1 Techno-economic sustainability

As shown in Figure 32, at 4.3-8.4 pence/kWh gas (CCGT) is the cheapest option (excluding incentives) but has the highest cost variability due to its high fuel component (approximately 74%). This is especially relevant given the continuing decline of UK gas production and increasing reliance on LNG from the international market. Traditional coal power is the second cheapest option at 5.3-9.5 pence/kWh. It also benefits from significantly lower vulnerability to fuel price fluctuations than gas, with fuel accounting for roughly 30% of total levelised cost. The central cost estimate for nuclear power, at 9.5 pence/kWh, is around 44% and 27% higher than gas and coal, respectively, although its potential range of 6.7-9.9 pence/kWh overlaps with those technologies. However, the bigger capital component of nuclear power (around 80% of total levelised cost), means that it becomes less attractive at higher discount rates. On the other hand, total cost is virtually insensitive to fuel price changes, and although conventional uranium reserves have a relatively short expected lifetime of around 80 years, this could increase to 675 years with phosphate resources and over 34,000 years if fast reactors become widespread. This compares to 119 years for coal and 63 years for natural gas.

At 11.2-19.1 pence/kWh, wind power is significantly cheaper than PV (29.6-80.0 pence/kWh), although still much higher than the other options. This is in part due to the high operation and maintenance costs incurred as owners attempt to improve availability factors, which have recently been quite low at 81%. The incentives currently available to offshore wind total 8.2 p/kWh and compare to the 40.6 p/kWh available to PV until April 2012, which illustrates the fact that the indirect cost to consumers of making offshore wind competitive is 32.4 p/kWh lower than that of PV. Even now that residential PV incentives are decreasing to 21 p/kWh following a government review, offshore wind will still cost the consumer 12.8 p/kWh less.

Natural gas and coal power both have high economic and technical dispatchability. Gas power plants in particular are also quick to build and resistant to technological lock-in due to their relatively short lifetime of 20-30 years and high temperature heat production. Nuclear power is quite non-dispatchable, but this is mainly an economic issue rather than a technical one, caused by its large capital component discussed above. Consequently, partial load-following by nuclear plants is achievable depending on peak electricity prices. As wind is non-dispatchable, costs depend heavily on capacity factors, which should improve as newer, larger turbines become widespread. Solar PV is also non-dispatchable, but the fact that variations in output more closely match variations in electricity demand should mitigate this problem somewhat.

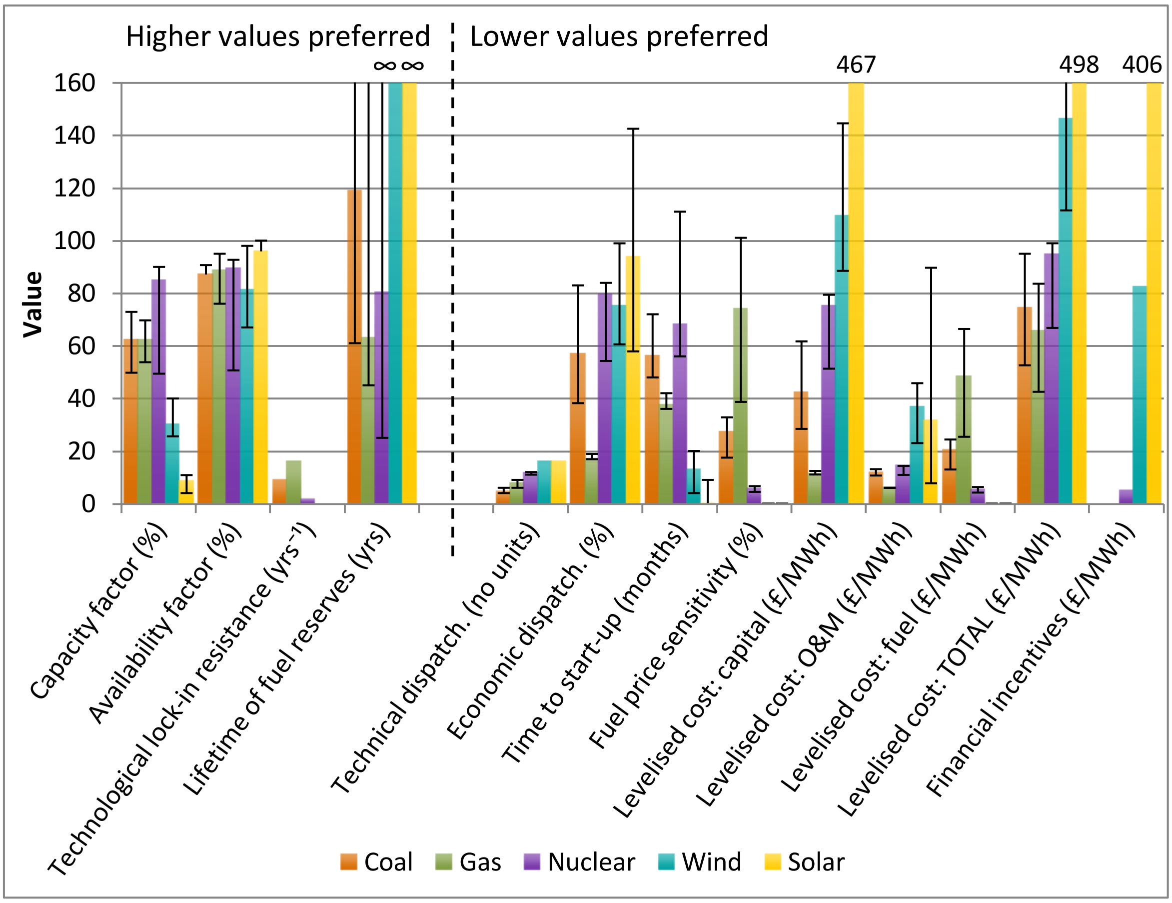

Figure 32: Techno-economic comparison of present-day technologies. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases apart from solar PV's *availability factor*, for which a current average is used. The *lifetime of fuel reserves* for offshore wind and solar power is effectively infinite. The central estimate of *levelised cost: capital* for solar power is £467/MWh. The central estimate of *levelised cost: TOTAL* for solar power is £498/MWh. The central estimate of *financial incentives* for solar power is £406/MWh. For full results, see Appendix 3**.**

9.1.1.2 Environmental sustainability

Environmentally, nuclear and offshore wind are the best two options for eight of the 11 indicators (see Figure 33). Wind only performs badly in freshwater and terrestrial eco-toxicity due to its high metal requirements. Nuclear power also performs worst in freshwater eco-toxicity due to emissions of heavy metals from uranium mill tailings. Aside from global warming and ozone layer depletion potential, natural gas is a sustainable environmental option, having the lowest freshwater, marine and terrestrial eco-toxicity potentials. However, its energy security contribution increasingly depends on LNG, the use of which could increase global warming potential by 36% to 496 g CO_2 eq./kWh. Coal is the least sustainable option for seven of 11 life cycle environmental indicators, including global warming potential. PV also performs relatively poorly for most impacts, having the highest ozone layer depletion potential and the second worst result in five of the remaining 10 indicators. This is mainly due to the relatively low insolation in the UK compared to countries like Spain and the USA, resulting in high resource requirements being badly balanced against low electrical output. Many of these results can be improved significantly (around 25% on average) by recycling, as most impacts are accrued during resource extraction and processing. However, even then PV only becomes one of the best two options in terms of freshwater and terrestrial eco-toxicity potentials: other impacts remain higher than those of nuclear, gas or offshore wind depending on the indicator.

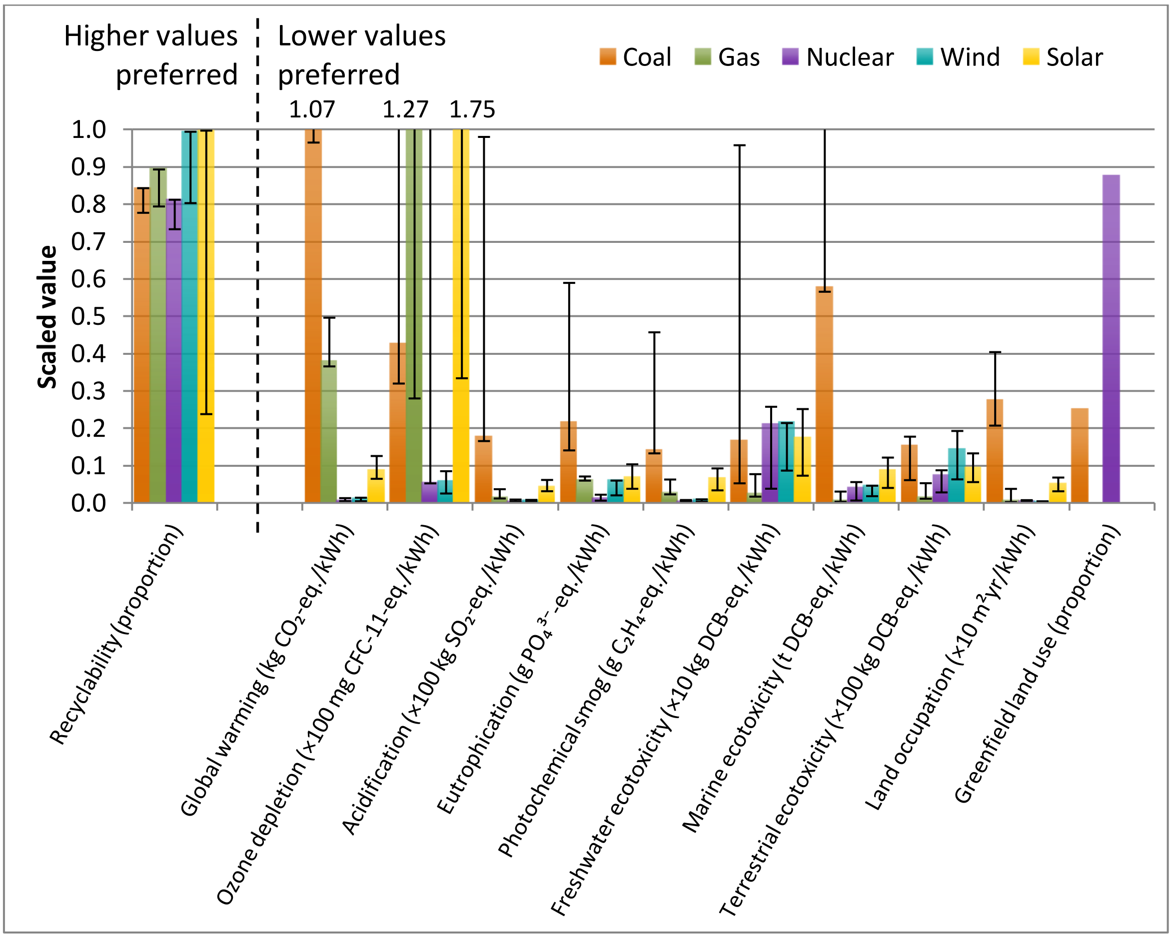

Figure 33: Environmental comparison of present-day technologies. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Bar height represents the central estimate in all cases. The central estimate of *global warming* for coal power is 1.07 kg CO_2-eq./kWh. The central estimate of *ozone depletion* for gas power is 0.0127 mg CFC-11-eq./kWh (1.27 on the graph's scaled *y* axis). The central estimate of *ozone depletion* for solar power is 0.0175 mg CFC-11-eq./kWh (1.75 on the graph's scaled *y* axis). For full results, see Appendix 3**.**

9.1.1.3 Social sustainability

Solar PV provides the highest employment of the five options (around 650 person-years/TWh), but consequently the most worker injuries: an order of magnitude more than either gas or nuclear power (see Figure 34). PV also has the second highest human toxicity potential and highest depletion of abiotic elements, exceeding the next worst option (offshore wind) by a factor of 15. Offshore wind is the second best option in terms of employment, providing 368 person-years/TWh. The coal life cycle provides the third highest employment (191 person-years/TWh), but 68% of this is in mining and, consequently, worker injury rates are relatively high: 8.3 times higher than those of the best option, gas power. Moreover, large accident fatalities for coal power are the highest of all options considered at 20.7 per TWh, four times higher than the next worst option (natural gas). Coal is also by far the worst option in terms of fossil fuel depletion and diversity of fuel supply, the latter mainly due to over-reliance on imports from Russia.

Natural gas provides the lowest employment (62 person-years/TWh) and causes relatively high fossil fuel depletion. For other sustainability aspects, however, gas performs extremely well, having the lowest human toxicity potential, worker injuries and depletion of elements. Its human toxicity potential is particularly good, being 93% lower than the second best option (offshore wind). Nuclear power has the second lowest life cycle employment (81 person-years/TWh), the highest health impact from radiation and arguably the greatest intergenerational impact, producing ~6000 m^3 of waste requiring geological storage per reactor lifetime. However this should be weighed against the intergenerational impact of climate change, for which nuclear is the best option with an impact around 170 times lower than that of coal power. Nuclear power also has the potential to cause the highest number of fatalities in a single incident (around 49,000), although in terms of the rate of large accident fatalities it is the best option, causing nearly 17,000 times fewer fatalities than the coal life cycle (0.00122 c.f. 20.7 fatalities/PWh). In addition, nuclear scores highly for the energy security indicators.

Offshore wind is a middle-ranking option in terms of worker injuries and human toxicity potential and, being fuelless in the conventional sense, in some respects it increases energy security. However, its non-dispatchability potentially necessitates increased grid-level reserve capacity. Offshore wind has few intergenerational equity issues, apart from non-fossil resource depletion, although even this is 93% lower than that of PV.

Regarding the relative human toxicity potentials of the technologies, it should be noted that there is currently a disagreement between LCA impact methodologies which affects the certainty of the results. Following recent updates to the Ecoinvent database [204] and the CML methodology [59, 139] used in this study, nuclear and solar PV appear to have the highest human health impacts (as discussed above). This same trend is observed using the IMPACT2002+ methodology [348]. However, aerial emissions from coal combustion give coal power the highest human health impact according to the Eco-indicator 99 [60], EDIP2003 [349] and RECIPE [350] methodologies. This uncertainty suggests that further analysis is necessary in this area (see Section 10.3 – recommendations for further work). Until then, the ranking of these technologies in terms of human toxicity should be viewed as tentative.

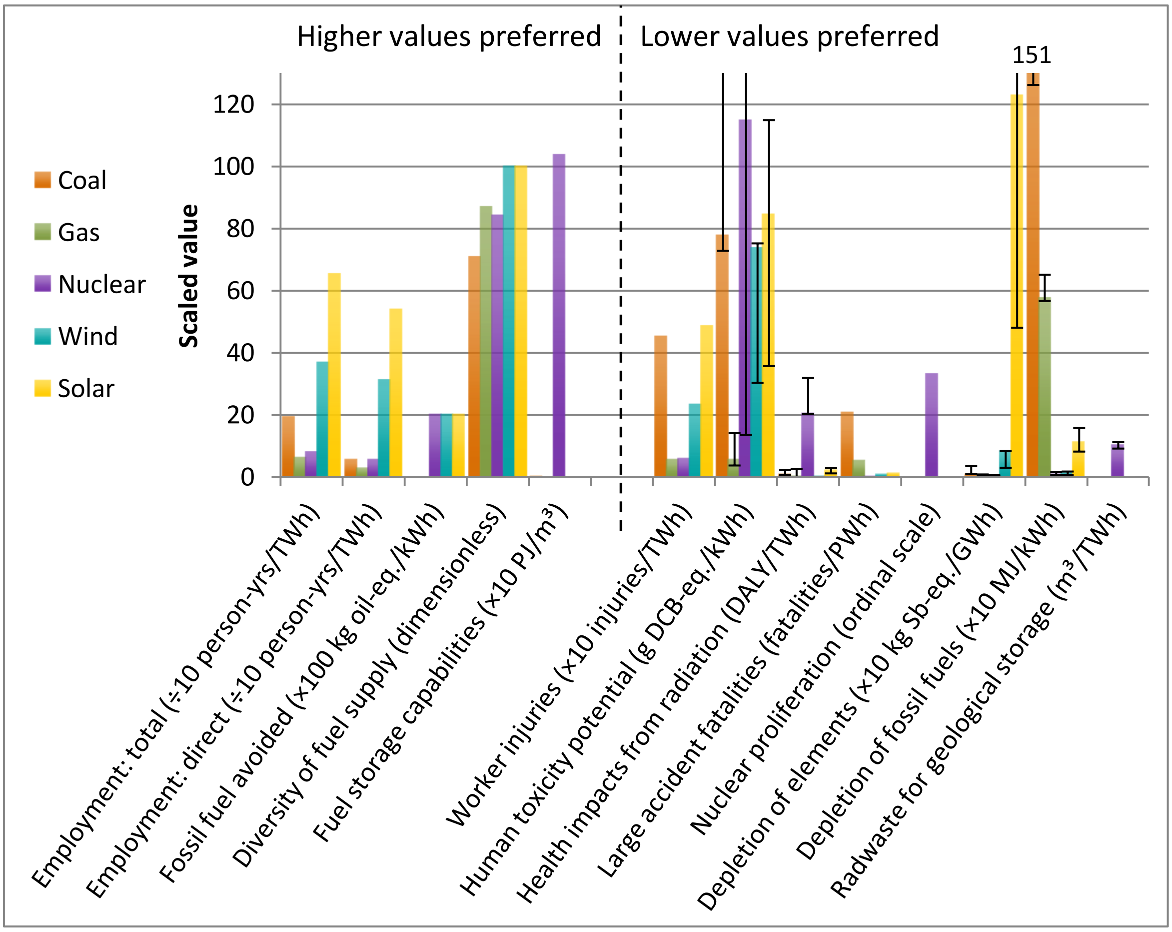

Figure 34: Social comparison of present-day technologies. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. Bar height represents the central estimate in all cases except *radwaste for geological storage*, for which the bar height represents the average value for the AREVA EPR and Westinghouse AP1000. The central estimate of *depletion of fossil fuels* for coal power is 15.1 MJ/kWh (151 on the graph's scaled *y* axis). For full results, see Appendix 3**.**

9.1.1.4 Summary of present-day technology comparison

Table 38 shows the ranking of each technology against each indicator as well as its summed rank for groups of indicators. In the absence of real indicator weightings such as those that would be applied in multi-criteria decision analysis (MCDA), this is an attempt to summarise the comparison of the five technologies, assuming that all indicators are of equal importance. In reality, the relative importance of each indicator will not be equal and will vary depending on stakeholder perspective. This is therefore a very simplistic analysis. It takes no account of the weightings stakeholders may place on individual impacts. Moreover, the total score takes no account of the fact that the environmental group has the fewest indicators, which biases the result in favour of techno-economic and social impacts. Finally, the exercise does not account for the distribution of individual indicator scores between different options. A more thorough ranking of technologies using MCDA is beyond the remit of this study but is suggested as a topic of further work in Section 10.3.

Bearing in mind the above limitations, natural gas appears to be the most sustainable option with a summed rank of 95. The second best option is offshore wind with 97, followed by nuclear power with 104, solar PV with 115 and coal power, the least sustainable option, with a summed rank of 125.

The analysis suggests that a stakeholder with a techno-economic bias would be likely to select either natural gas or coal as their preferred option due to their summed ranks of 32 and 33, respectively in the techno-economic section compared to 40 and above for the other options. Conversely, an environmentally biased perspective would likely favour nuclear, offshore wind or gas power with their summed ranks of 25, 26 and 27, respectively. These compare to 36 for solar PV and 48 for coal power. Finally, from the social perspective offshore wind appears to be preferable with a summed rank of 27, the next best option being solar PV.

Table 38: Ranking of each technology against each indicator

Category	Issue addressed	Indicator	Unit	Technology: Nuclear (PWR)	Natural gas (CCGT)	Coal (subcritical pulverised)	Wind (offshore)	Solar (PV)
Techno-economic	Operability	1. Capacity factor (power output as a percentage of the maximum possible output)	Percentage (%)	1	3	2	4	5
		2. Availability factor (percentage of time a plant is available to produce electricity)	Percentage (%)	2	3	4	5	1
		3. Technical dispatchability (ramp-up rate, ramp-down rate, minimum up time, minimum down time)	Summed rank	3	2	1	5	5
		4. Economic dispatchability (ratio of capital cost to total levelised generation cost)	Dimensionless	4	1	2	3	5
		5. Lifetime of global fuel reserves at current extraction rates	Years	4	5	3	1	1
	Technological Lock-in	6. Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/thermochemical H_2 production) and operational lifetime	$Years^{-1}$	3	1	2	5	5
	Immediacy	7. Time to plant start-up from start of construction	Years	5	3	4	2	1
	Levelised Cost of Generation	8. Capital costs	Pence/kWh	3	1	2	4	5
		9. Operation and maintenance costs	Pence/kWh	3	1	2	5	4
		10. Fuel costs	Pence/kWh	3	5	4	1	1
		11. Total levelised cost	Pence/kWh	3	1	2	4	5
	Cost Variability	12. Fuel price sensitivity (ratio of fuel cost to total levelised generation cost)	Dimensionless	3	5	4	1	1

	Financial Incentives	13. Financial incentives and assistance (e.g. ROCs, taxpayer burdens)	Pence/kWh	3	1	1	4	5
			Techno-economic summed rank	**40**	**32**	**33**	**44**	**44**
Environmental	**Material Recyclability**	14. Recyclability of input materials	Percentage (%)	5	3	4	2	1
	Water Eco-toxicity	15. Freshwater eco-toxicity potential	kg 1,4 DCB‡ eq./kWh	4	1	2	5	3
		16. Marine eco-toxicity potential	kg 1,4 DCB‡ eq./kWh	2	1	5	3	4
	Global Warming	17. Global warming potential (GHG emissions)	kg CO_2 eq./kWh	1	4	5	2	3
	Ozone Layer Depletion	18. Ozone depletion potential (CFC and halogenated HC emissions)	kg CFC-11 eq./kWh	1	4	3	2	5
	Acidification	19. Acidification potential (SO_2, NO_x, HCl and NH_3 emissions)	kg SO_2 eq./kWh	1	3	5	2	4
	Eutrophication	20. Eutrophication potential (N, NO_x, NH_4^+, PO_4^{3-} etc.)	kg PO_4^{3-} eq./kWh	1	3	5	2	4
	Photochemical Smog	21. Photochemical smog creation potential (VOCs and NO_x)	kg C_2H_4 eq./kWh	1	3	5	2	4
	Land Use & Quality	22. Land occupation (area occupied over time)	m^2yr/kWh	2	3	5	1	4
		23. Greenfield land use (proportion of new development on previously undeveloped land relative to total land occupied)	Percentage (%)	5	1	4	1	1
		24. Terrestrial eco-toxicity potential	kg 1,4 DCB‡ eq./kWh	2	1	5	4	3
			Environmental summed rank	**25**	**27**	**48**	**26**	**36**
Social	**Provision of Employment**	25. Direct employment	Person-years/GWh	3	5	4	2	1
		26. Total employment (direct + indirect)	Person-years/GWh	4	5	3	2	1
	Human Health Impacts	27. Worker injuries	No. of injuries/TWh	2	1	4	3	5
		28. Human toxicity potential (excluding radiation)	kg 1,4 DCB‡ eq./kWh	5	1	3	2	4
		29. Human health impacts from radiation (workers and population)	DALY¥/GWh	5	2	3	1	4
	Large Accident Risk	30. Fatalities due to large accidents	No. of fatalities/GWh	1	4	5	2	3
	Local Community Impacts	31. Proportion of staff hired from local community relative to total direct employment	Percentage (%)	-	-	-	-	-
		32. Spending on local suppliers relative to total annual spending	Percentage (%)	-	-	-	-	-
		33. Direct investment in local community as proportion of total annual profits	Percentage (%)	-	-	-	-	-

Human Rights and Corruption	34. Involvement of countries in the life cycle with known corruption problems (based on Transparency International Corruption Perceptions Index)	Score (0-10)	-	-	-	-	-
Energy Security	35. Amount of imported fossil fuel potentially avoided	toe/kWh	1	5	5	1	1
	36. Diversity of fuel supply mix	Score (0-1)	4	3	5	1	1
	37. Fuel storage capabilities (energy density)	GJ/m^3	1	3	2	5	5
Nuclear Proliferation	38. Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	Score (0-3)	5	1	1	1	1
Intergenerational Equity	39. Use of abiotic resources (elements)	kg Sb eq./kWh	2	1	3	4	5
	40. Use of abiotic resources (fossil fuels)	MJ/kWh	1	4	5	2	3
	41. Volume of radioactive waste to be stored	m^3/kWh	5	1	1	1	1
	42. Volume of liquid CO_2 to be stored	m^3/kWh	-	-	-	-	-
		Social summed rank	**39**	**36**	**44**	**27**	**35**
		TOTAL SUMMED RANK	**104**	**95**	**125**	**97**	**115**

‡DCB – dichlorobenzene; ¥DALY – disability-adjusted life year

9.1.2 Sustainability assessment of the current UK electricity mix

In demonstrating the application of the developed sustainability assessment framework and indicators to the current UK electricity mix, it is only possible to consider technologies for which full results have been compiled during the course of this research. This means that it is necessary to simplify the actual electricity mix by omitting the remaining technologies that currently contribute to the mix. These are as follows (calculated from [16] based on the mix in 2009):

- Nuclear (AGR and Magnox reactors) (estimated at 16%[35])
- Biomass (3.1%)
- Onshore wind (2%)
- Hydro (natural flow) (1.4%)
- Oil (1.2%)
- Gas (open cycle gas turbine) (1.2%)
- Hydro (pumped storage) (1%)

Thus a total of 26% of the UK electricity mix is unaccounted for, meaning the results in their current state carry additional uncertainty and are illustrative only. However, nuclear power from AGRs and Magnox reactors, as well as oil power plants, will rapidly decrease their contributions in the next decade, making their omission arguably less important. Given the constraints of available data, nuclear power from AGR and Magnox power stations is described using the PWR dataset, while onshore wind is described using the offshore wind dataset, allowing 92% of the electricity mix to be accounted for. The remaining technologies are omitted completely, but are discussed below where appropriate. In producing illustrative results for the baseline year, the deficit of 8% left by the omitted technologies is accounted for by scaling up the contribution of the available technologies proportionately, giving a mix as follows:

[35] Nuclear power accounted for 18.4% of electricity generation in 2009 [16]. However, the output of individual nuclear power stations is not available, therefore the contribution of non-PWRs has been estimated by subtracting the production of Sizewell B (the only current PWR), assuming 85% capacity factor, from total nuclear production.

Table 39: Approximated electricity generation mix for the UK, comprising only modelled technologies (based on the mix in 2009)

Technology	Contribution to electricity generation mix in GWh (%)
Natural gas (CCGT)	175,795 (46.8)
Coal (subcritical pulverised)	114,232 (30.4)
Nuclear (PWR)	75,455 (20.1)
Wind (offshore)	10,160 (2.7)
Solar (domestic PV)	22 (0.01)
TOTAL	**375,663 (100)**

The following sections present and discuss the assessment results for the present-day UK electricity mix based on the mix shown in Table 39 and the data given in Section 9.1.1 and Appendix 3. The summary results are shown both per year and per unit of electricity generated in Figure 35-Figure 40; full results can be found in Appendix 5.

9.1.2.1 Techno-economic sustainability

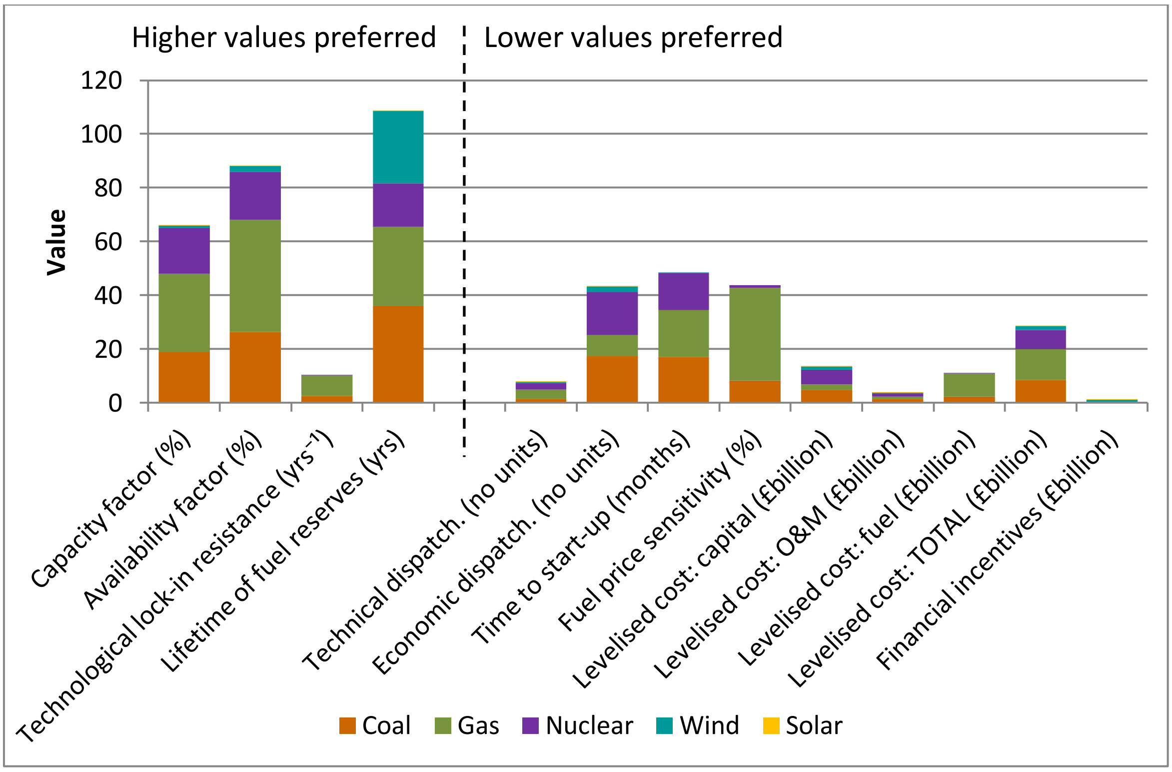

Figure 35: Techno-economic assessment of the present-day UK electricity mix (based on that of 2009) expressed per year. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. For full results, see Appendix 5.

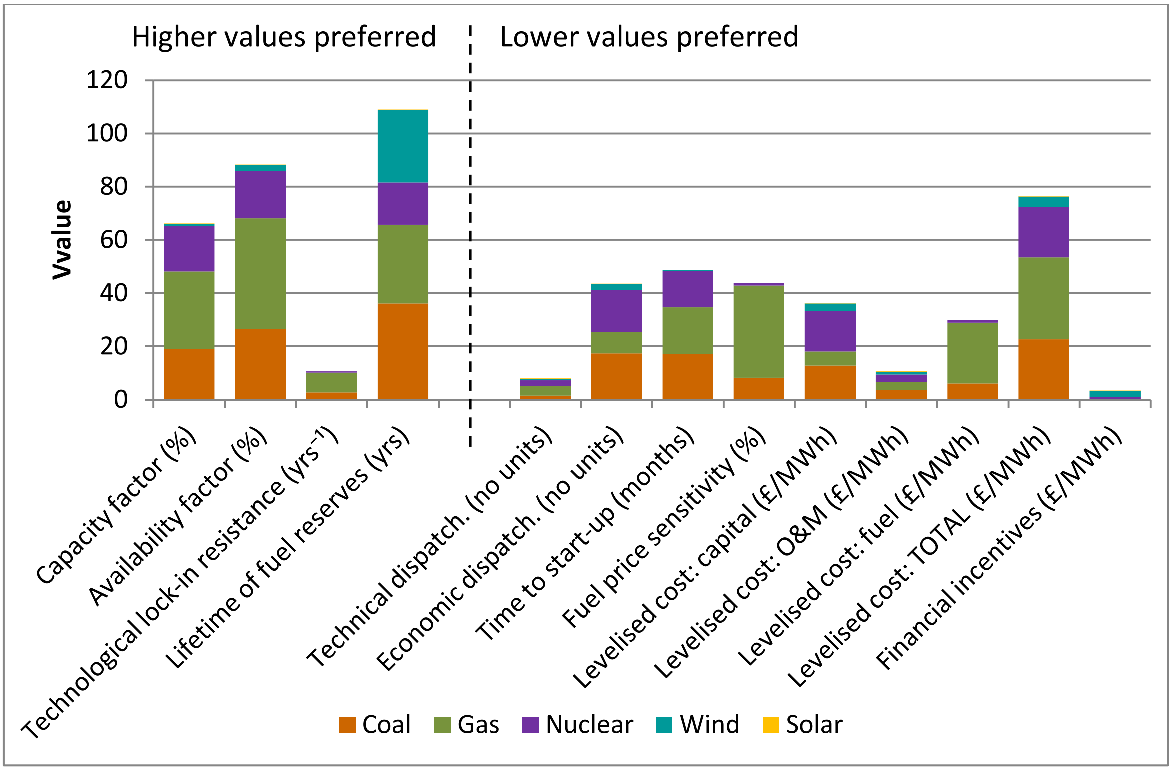

Figure 36: Techno-economic assessment of the present-day UK electricity mix (based on that of 2009) expressed per unit of electricity generated. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. For full results, see Appendix 5**.**

The techno-economic results shown in Figure 35 and Figure 36 (see Appendix 5 for details) are reflective of the fact that coal and gas dominate electricity production in present-day UK: the current mix has representative capacity and availability factors of 66% and 88%, respectively, illustrating the load-following regimes and high reliability of coal and gas power plants. Technological lock-in resistance is rated at 10.5 yr^{-1} with about 70% of that being due to the short lifespan (20-30 years) and high temperature heat of natural gas plants. The effective lifetime of fuel reserves is 109 years, intermediate between that of coal and gas. However, as the figure shows, this is increased somewhat by the presence of wind power and its effectively infinite reserve lifetime (here capped at 1000 years to enable calculation).

The average technical dispatchability of the current mix scores 7.79, while its economic dispatchability is 43.2. These are relatively good ratings (lower scores being better) reflecting the fact that coal and gas plants are well suited to load-following (technical dispatchability scores of 4.7 and 7.7, respectively, and economic dispatchabilities of 56.9 and 17.0).

In terms of cost, the current mix represents a levelised cost of generation of 7.6 pence/kWh (or £28.7 billion per year) with a relatively high sensitivity to fuel price fluctuations at 43.9%. As shown in the figures, 79% of this fuel price sensitivity is attributable to gas power, a point which is illustrated by the fact that recent years (2005-2012) have seen rapidly rising electricity prices in direct response to gas price increases (although other factors also contribute [see 351]). Current incentives available for electricity generators amount to approximately £1.2 billion per year, which equates to 4.3% of total electricity costs or 0.33 pence/kWh. Around two thirds (68%) of this incentive currently goes to wind power, although the use of the offshore wind dataset to describe all wind power exaggerates this figure as onshore wind receives fewer Renewables Obligation Certificates (see Section 7.1).

9.1.2.2 Environmental sustainability

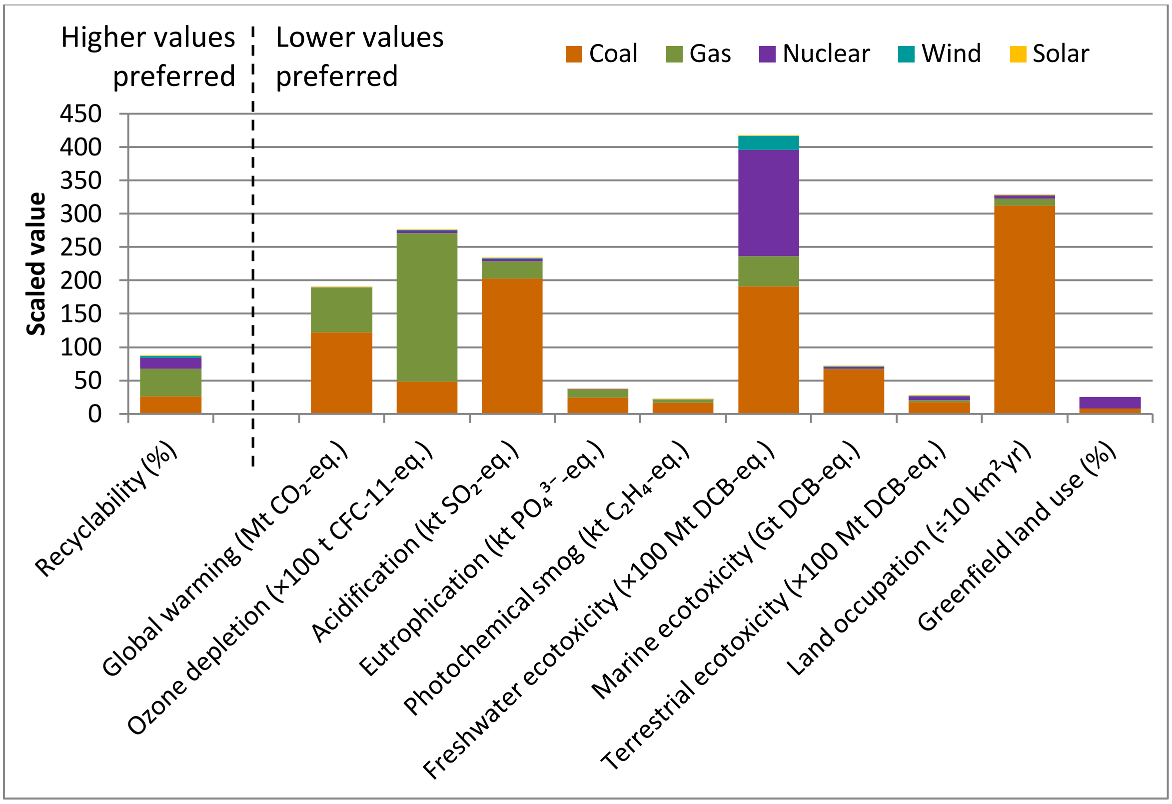

Figure 37: Environmental assessment of the present-day UK electricity mix (based on that of 2009) expressed per year. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. For full results, see Appendix 5.

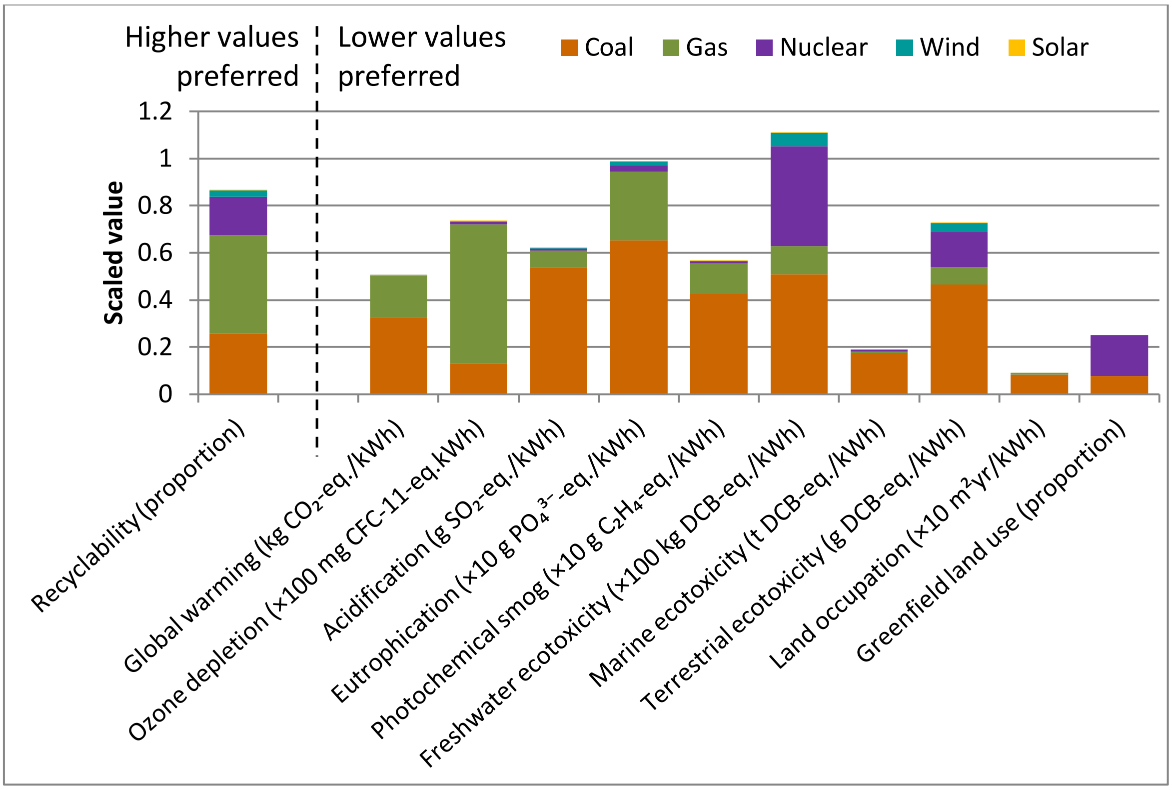

Figure 38: Environmental assessment of the present-day UK electricity mix (based on that of 2009) expressed per unit of electricity generated. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. For full results, see Appendix 5.

The results in Figure 37 and Figure 38 show that coal and gas cause a disproportionate amount of the total environmental impact: despite constituting 77% of the modelled mix, they account for almost all of seven impacts. For instance, 99.7% of the annual global warming potential of 189.7 Mt CO_2 eq. is caused by coal and gas power. The notable exception to this trend is freshwater eco-toxicity potential, for which 38% of a total impact of 4.2 Mt DCB eq./year (or 11.1 g DCB eq./kWh) is due to nuclear power. As discussed in Section 4.4.2.7, this is because uranium milling has particularly high long-term emissions of heavy metals.

According to DECC, in 2009 power stations in the UK emitted 151 Mt CO_2 [352] or around 400 g CO_2/kWh but these results show that, with the inclusion of other greenhouse gases and all stages of the electricity production life cycle, the estimated global warming potential in 2009 was around 190 Mt CO_2 eq. or 505 g CO_2 eq./kWh.

Around 86% of the current UK fleet can potentially be recycled at the end of its life, although this is likely overestimated due to the use of the nuclear (PWR) dataset to describe all nuclear power currently in the UK: the recyclability of PWRs, discussed in Section 4.3.2.1, is likely higher than the AGRs that make up most of the current UK fleet due to, for example, higher volumes of irradiated graphite in AGRs. As such, the figure of 86% should be seen as representative of what would happen if current nuclear capacity was replaced with PWRs.

Ozone layer depletion potential for the present-day electricity mix is estimated at 7.3×10^{-9} kg CFC-11 eq./kWh, totalling 2.8 t CFC-11 eq. per year. Most of this impact (81%) is due to the natural gas power life cycle and its use of fire retardants, as discussed in Section 5.4.2.3. Natural gas power also contributes significantly (30%) to the total eutrophication potential of the UK electricity mix, which is estimated at 9.9 g PO_4^{3-} eq./kWh or around 37 kt PO_4^{3-} eq. per year.

The other environmental impacts are dominated by coal power: acidification potential is 233 kt SO_2 eq./year (0.62 g SO_2 eq./kWh) of which 87% is attributable to coal; photochemical smog potential, at 21.3 kt C_2H_4 eq./year (0.056 g C_2H_4 eq./kWh) is 75% due to coal; over 90% of the total marine eco-toxicity potential (70.8 Gt DCB eq./year; 188 kg DCB eq./kWh) is caused by the coal life cycle, as is 95% of the total land occupation of 3276 km^2 (0.0087 m^2yr/kWh).

In contrast to the above impacts, terrestrial eco-toxicity potential is at least in part dictated by the contribution of nuclear power to the mix: of a total impact of 273 kt DCB eq./year (or 0.73 g DCB eq./kWh), about 20% is due to nuclear power and 64% to coal power. The impact of the nuclear life cycle is, in this case, mainly caused by heavy metal emissions to air from uranium mill tailings (see Section 4.4.2.8). Finally, the greenfield land use result indicates that around 25% of all new build proposals involving the technologies assessed would take place on greenfield land.

9.1.2.3 Social sustainability

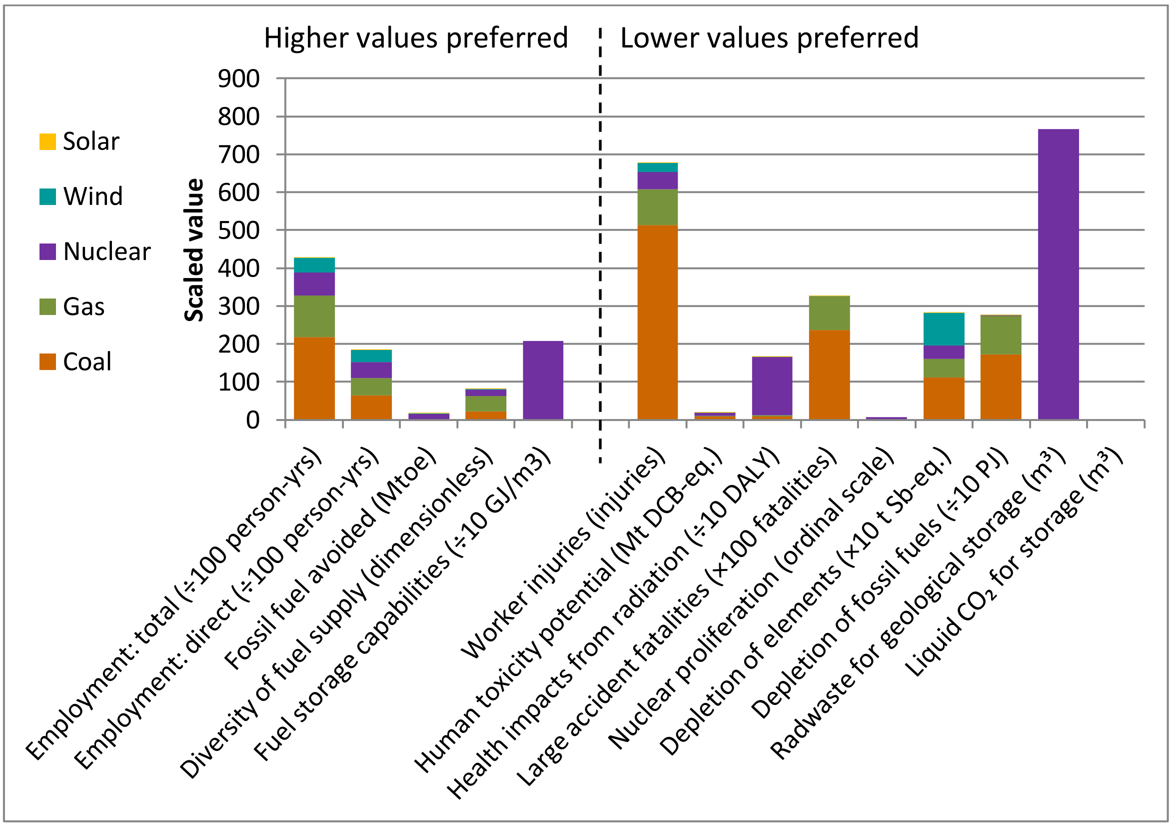

Figure 39: Social assessment of the present-day UK electricity mix (based on that of 2009) expressed per year. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. For full results, see Appendix 5.

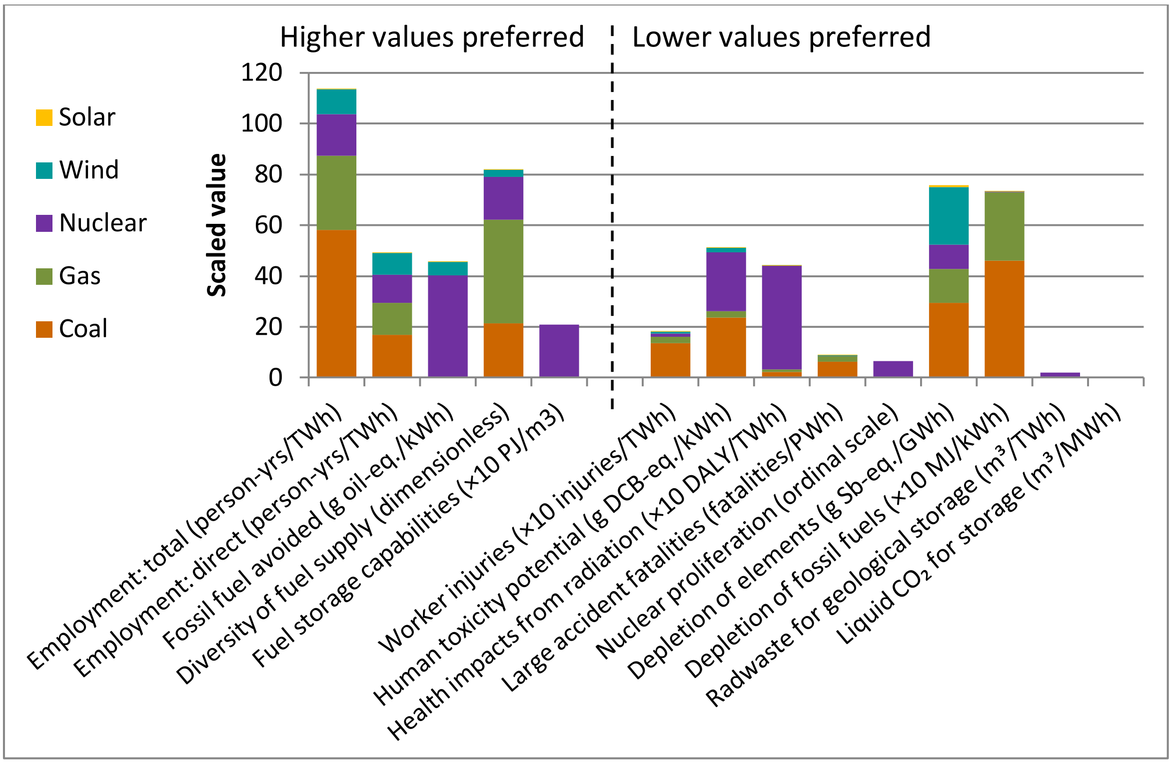

Figure 40: Social assessment of the present-day UK electricity mix (based on that of 2009) expressed per unit of electricity generated. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. For full results, see Appendix 5.

When all life cycle stages are included, UK electricity generation in 2009 provided 42,700 full-time-equivalent jobs (or 114 person-years/TWh). Of these, 21,800 are attributable to coal power which creates most of its employment (68%) in mining. Most of these jobs are therefore hazardous and outside the UK. Coal's contribution to worker injuries emphasises this: more than 500 injuries per year are attributable to coal out of a total of 677; the total injury rate associated with UK electricity is 1.8 injuries/TWh. The coal life cycle is also the cause of most (72%) of the large accident fatalities (although these only total 3.3 per year) with gas power making up a further 27%. Direct employment, which excludes labour in the fuel cycle, only amounts to 18,400 jobs with wind providing a disproportionately high percentage of these (17%, despite only providing 2.7% of electricity). This is a reflection of its high operation and maintenance requirements (see Section 7.4.3.1).

Approximately 1657 disability-adjusted life years (DALYs) are lost every year due to the electricity produced in the UK, or around 4.4 per TWh, 92% of them resulting from nuclear power. These DALYs are distributed internationally and through time, occurring over thousands of years, mainly due to emissions from uranium mill tailings (see Section 4.4.3.2). Nuclear power also accounts for a disproportionately high amount of the total human toxicity potential attributable to the electricity mix: of the 19.2 Mt DCB eq. emitted per year, 45% is caused by nuclear power. Again, this is mainly due to uranium mill tailings.

Two of the three energy security indicators are dominated by nuclear power's contribution: nuclear accounts for 88% of the 17 Mtoe of fossil fuel avoided each year by non-fossil technologies (or 45.6 g oil eq./kWh); it also constitutes over 99.9% of the average energy density of the fuels used in the electricity mix (2.1 PJ/m^3 on average). The overall diversity of fuel supplies for the UK electricity mix is rated at 81.8, which is lower than the individual rating for gas, nuclear, offshore wind or solar PV due to the poor diversity of coal supplies (see Section 6.4.3.5).

The intergenerational equity indicators show that wind power causes a disproportionately high depletion of elements: of the 28.4 t Sb eq. depleted per year (or 75.7 g Sb eq./GWh), 30% occurs in the wind power life cycle despite it only providing 2.7% of electricity. In terms of fossil fuel depletion, however, coal and gas account for 99.7% of the total (2750 PJ/year, or 7.3 MJ/kWh). The final intergenerational equity indicator measures the amount of radioactive waste produced requiring long-term storage: nuclear power creates around 770 m^3 per year, or 0.002 ml/kWh[36].

9.2 Assumed characteristics of technologies in future time periods

One of the aims of this project was to test the sustainability assessment framework and indicators by applying them to future electricity mixes as part of scenario analysis (see Section 9.3). Although scenario analysis has been used extensively for electricity generation in the UK [see 3, 29, 89], this has focused mainly on costs and climate change impacts over a limited number of life cycle stages (mostly the operation stage) and up to the year 2050. Therefore, the novelty of this work is at least three-fold: firstly, it applies for the first time a full life cycle approach to scenario analysis of electricity generation in the UK; secondly, it applies the most comprehensive set of sustainability indicators to date; and thirdly, it considers a time horizon up to 2070. The latter is chosen to better reflect the longevity of modern power plants, particularly nuclear reactors which have lifespans of 60 years. Additionally, the extra time allows grid composition to change radically while staying within reasonable build rates for individual

[36] It should be noted that this estimate is based on figures for new pressurised water reactors (PWRs). The current UK fleet is composed mainly of advanced gas-cooled reactors (AGRs), for which waste production has not been quantified in this study. The result should therefore be seen as representative of what would happen if existing nuclear capacity was replaced with new PWRs.

technologies. However, in order to consider future electricity mixes, the characteristics of electricity technologies for future time periods must first be defined. The assumptions made for these purposes are outlined below.

Coal (subcritical pulverised), natural gas (CCGT) and nuclear power (PWR, once-through cycle) are relatively mature technologies. Technological changes occurring over the coming decades should therefore be modest. Moreover, any changes that do occur will take time to affect the electricity mix as old plants must first reach the ends of their lives. Offshore wind, on the other hand, is an immature technology for which the UK is the current world leader in terms of installed capacity (1858 MW at the time of writing, representing about half of the worldwide total [299]) and its characteristics should therefore change more quickly. Solar PV is also immature with global installed capacity speculated to increase more than 100-fold between 2010 and 2050 [353]. Given the immaturity and accelerating uptake of these two technologies, significant improvements can be expected in the medium term. As a result, their future characteristics have been significantly modified as discussed below.

In addition to the five technologies discussed above (and in Chapters 4-8), coal with carbon capture and storage (CCS) may play a significant role in the future UK electricity mix. There are no large scale coal CCS plants currently operating, but any new coal plant proposed in the UK must have CCS fitted to at least 300 MW of its capacity [354]; development of CCS is also supported by the government’s plans to demonstrate the technology before 2020, including £1 billion of capital subsidy [30]. Illustrative figures for coal CCS have therefore also been added to the analysis, as described below.

9.2.1 Techno-economic assumptions

Of the techno-economic factors, the changes assumed between the present and 2070 apply to the levelised costs of each technology, the lifetime of fuel reserves and, for offshore wind power, capacity and availability factors. The financial incentives indicator has not been used in the scenario analysis as future policy is completely unknown. All other data are assumed constant as they are not expected to change significantly in the future, the exceptions being fuel price sensitivity and economic dispatchability which are both ratios of cost components (see Section 3.2.1) and therefore change automatically with levelised costs. Future techno-economic data for all technologies are given in Appendix 7.

9.2.1.1 Capacity and availability factors

Capacity factor

As discussed in Sections 4.4.1.1, 5.4.1.1, 6.4.1.1 and 8.4.1.1, the capacity factor of most technologies is not expected to change significantly. This assertion is based on all other things being equal; in reality, capacity factors of gas and coal plants will likely change as their operators respond to changes in grid composition. However, this is clearly dependent on the rest of the energy mix and cannot be predicted due to other uncertainties such as the level of demand side management. Wind power is the only technology for which capacity factors are expected to change considerably (see Section 7.4.1.1): in this analysis, they are assumed to increases from the current 30% to 50% by 2035 as turbine sizes increase and farms are sited further offshore exploiting more regular wind patterns. This is in good agreement with projections by RenewableUK which suggest average capacity factors of 40% by the early 2020s [355].

Availability factor

As for capacity factors, only wind power is expected to improve its availability (as discussed in Section 7.4.1.1). Availability factors are assumed to increase from the present-day 81.4% to 95% by 2020 via industrial experience. This latter figure is a conservative implementation of RenewableUK's expectations of 98% [313].

9.2.1.2 Lifetime of fuel reserves

Fuel reserve lifetime is only applicable to nuclear, gas and coal. Reserves are assumed to be constant through time, meaning reserve lifetimes simply decrease according to the number of years from the present. For instance, a lifetime of 80 years in 2010 decreases to 70 years by 2020. This assumption is not likely to be accurate as unknown factors play an important role in estimating reserve lifetimes: global demand for each fuel and new extraction techniques and reserve discoveries cannot be predicted in advance, meaning future estimates are highly uncertain.

Fuel reserve lifetimes for wind and solar power, despite essentially being infinite (see Sections 7.3.1.1 and 8.3.1.1), have been capped at 1000 years to enable calculation of effective reserve lifetimes for the whole electricity mix.

9.2.1.3 Levelised cost of generation

The future costs of nuclear, coal and natural gas power are taken from the same source as the that discussed in Chapters 4-8: Mott MacDonald 2010 [201] at 10% discount rate. This study has been selected because it is UK-specific and recent, as discussed in Section 4.3.1.4. A start date of 2023 is as far into the future as this study predicts and, given the maturity of these three technologies, this cost estimate is adopted for all years between 2020 and 2070. The assumptions made by Mott MacDonald are therefore inherited here, but are broadly in line with those in the rest of this study, as shown below in Table 40. The data also assume that any first-of-a-kind premium associated with new build no longer applies by 2023 due to prior industrial learning. In line with earlier chapters, the carbon tax applied by the authors has been removed from their estimates in order to illustrate basic costs without uncertain penalty or subsidy. It should be noted here that the lack of cost projections for these technologies beyond a 2023 start date is partly due to the huge uncertainty in coal and gas prices out to 2070. This is a problem inherent in scenario analysis, particularly when projecting over a time frame of nearly 60 years. Further work in this area could provide considerable improvements to the accuracy of future prices for these technologies.

Table 40: Main assumptions made by Mott MacDonald [201] in future cost estimation

	Construction time (yrs)	Plant availability (%)	Plant lifetime (yrs)	Fuel costs
Gas	2.5	91.2	30	58 pence/therm rising to 74 in 2030 (based on analysis by DECC)
Coal	4.0	90.2	40	$147/tonne declining to 80 in 2030 (based on analysis by DECC)
Nuclear	5.0	90.8	60	not stated by author

In the case of offshore wind, solar PV and coal CCS, more significant cost reductions are expected. Future costs for these technologies have therefore been modelled using learning rates from the IEA's Technology Roadmaps [353, 356], Arup 2011 [333] and Rubin et al. 2007 [357], as these represent the best available data. The learning rates that have been applied in the central case are 12% for offshore wind (as suggested by Arup based on UK data [333]), 18% for solar PV (as suggested by IEA [353]) and, in the case of coal CCS, an average cost was derived using learning rates of 3.5% for post-combustion technology and 4.9% for IGCC (based on analysis by Rubin et al. [357]). Appendix 6 describes in detail the derivation of future costs in this study, as well as sensitivity analyses and other available estimates of future costs in literature.

The cost estimates taken from Mott MacDonald and those calculated in this study are shown with the other future techno-economic data in Appendix 7.

9.2.2 Environmental assumptions

Changes to the recyclability and LCA impacts between the present and 2070 have been treated as discussed below. The greenfield land use indicator has not been used in future scenarios as its values cannot be predicted. Future environmental data for all technologies are given in Appendix 7.

9.2.2.1 Material recyclability

Recyclability is assumed constant over time as it illustrates the potential recyclability of plant components rather than the actual mass recycled (which will likely improve with time). In the absence of more detailed data, coal CCS power stations are assumed to be as recyclable as non-CCS coal plants due to their many shared components: the extra equipment required for CCS is much smaller than, and of similar material composition to, the rest of the plant.

9.2.2.2 Other environmental issues

Other environmental impacts are, in the case of nuclear, coal and gas power, assumed to be constant over time due to their technological maturity. This a simplification, as follows: in reality, life cycle impacts will change in future as, for example, the electricity used during component manufacture is increasingly sourced from non-fossil technologies. However, accounting for this would necessitate assumptions about future electricity mixes not only in the UK but in all countries from which materials are sourced. Such global projections are beyond the remit of this work. Moreover, such changes do not affect the impacts of power plants built in the immediate future – power plants which will be part of the electricity mix for decades. In the case of coal, since no new plants can be built in the UK it would not be appropriate to change anything other than the coal supply mix, which cannot be predicted.

Transportation is another major background process whose impacts will change in future, but this has not been accounted for in future modelling of any technology. This is to limit the number of assumptions that must be made. However, transport typically forms only a small component of the life cycle impacts of electricity generation, so this omission is thought not to have a major effect.

In contrast to nuclear, coal and gas, the LCA impacts of offshore wind and solar PV are assumed to change to some extent through time due to their immaturity. In the case of offshore wind power, the central estimates for all impacts in the future are based on the more advanced technologies modelled as part of LCA sensitivity analysis (see Section 7.3.2.2 and Appendix 3), as follows:

- **2020**: 3 MW turbines, monopile foundations, capacity factor of 40%
- **2035**: average of 3 MW and 5 MW turbines, both monopile foundations, both with capacity factors of 50%
- **2050**: 5 MW turbines, monopile foundations, capacity factor of 50%
- **2070**: same as 2050 (reflecting the slowing of improvement as technologies mature [357], as well as uncertainty over potential technological developments in this time period)

This leads to a central GWP estimate for the year 2050 of 4.73 g CO_2 eq./kWh (see Appendix 7), showing a rate of reduction in good agreements with other studies such as the NEEDS project [358].

In the case of solar PV, the LCA modelling discussed in Section 8.3.2.2 (and shown in Appendix 3) has been altered by reducing the area of panels required per installation in line with solar panel efficiency improvements expected by the IEA [353]. The mix of PV technologies is assumed to be constant. This is acknowledged to be unrealistic because newer technologies such as copper-indium-gallium-selenide (CIGS) will likely become more widespread than traditional mono-crystalline Si panels and will themselves be surpassed by future ‘third generation’ technologies in time. However, given a lack of robust future projections, this is an unavoidable simplification. Thus, it is likely that, combined with the lower insolation experienced in the UK relative to most of Europe, emission reductions in this study are lower than in some other studies including NEEDS. For instance, in 2050 this work estimates the GWP of solar PV at 28-68 g CO_2 eq./kWh (see Section 18.5 in Appendix 7) compared to the range under German conditions in NEEDS of 3.6-11 g CO_2 eq./kWh [358]. It should be noted, however, that NEEDS consider much larger installations than those assessed in this study (420-46,600 kWp c.f. 3 kWp) meaning lower emissions can be expected due to increasing returns to scale (via sharing of components and other resources). Additionally, NEEDS assumes higher capacity factors than those suitable for the

UK (see Section 8.4.1.1). Nevertheless, in order to improve confidence in this area, further work on future thin-film solar technologies under UK conditions is recommended (see Section 10.3).

Table 41 shows the future efficiencies and required panel areas assumed in this modelling. Data in 2070 are assumed to be the same as those of 2050 in order to reflect the slowing of improvement as photovoltaic technology matures. It is acknowledged that solar PV will likely continue to improve beyond 2050 but the rate of improvement is highly uncertain, as reflected in the IEA's decision to forecast only to 2030 [353]. Further work in this area is therefore recommended (see Section 10.3)

Table 41: Future efficiencies and panel areas assumed for solar photovoltaics

Year	Type	Panel efficiency	Area required for 3 kWp (m^2)	Source
~2005	mono-Si	14.0%	21.429	Jungbluth et al 2008 [335]
	multi-Si	13.2%	22.727	
	ribbon-Si	12.0%	25.000	
	amorphous-Si	6.5%	46.154	
	CIS	10.7%	28.037	
	CdTe	7.6%	39.474	
2020	mono-Si	23.0%	13.043	IEA 2010 [353]
	multi-Si	19.0%	15.789	
	ribbon-Si[1]	n/a	n/a	
	amorphous-Si	12.0%	25.000	
	CIS	15.0%	20.000	
	CdTe	14.0%	21.429	
2030	mono-Si	25.0%	12.000	
	multi-Si	21.0%	14.286	
	ribbon-Si[1]	n/a	n/a	
	amorphous-Si	15.0%	20.000	
	CIS	18.0%	16.667	
	CdTe	15.0%	20.000	
2050	mono-Si	29.0%	10.345	Extrapolated from the trend suggested by IEA 2010 [353].
	multi-Si	25.0%	12.000	
	ribbon-Si[1]	n/a	n/a	
	amorphous-Si	21.0%	14.286	
	CIS	24.0%	12.500	
	CdTe	17.0%	17.647	

[1] No efficiency projections were available for ribbon-Si. Therefore, in LCA modelling, CIGS was used in its place.

Environmental impacts for coal CCS are based on models from the NEEDS project [245], as they reflect the most comprehensive available data. Various results are available from this database, covering possible impacts under five scenarios in the years 2025 and 2050. The results are used in this study in a manner that approximates gradual progression through time, as follows:

- **2020**: NEEDS 2025 worst-case ("pessimistic/business-as-usual" 500 MW plant, post combustion CCS, 400km of pipeline and storage in a 2500m depleted gas field)
- **2035**: average of NEEDS 2025 best-case ("very optimistic/renewable" 500 MW plant, oxy-fuel CCS, 200km of pipeline and storage in an 800m aquifer) and 2050 worst-case ("pessimistic/business-as-usual" 500 MW plant, post combustion CCS, 400km of pipeline and storage in a 2500 m depleted gas field).
- **2050**: average of NEEDS 2050 best-case ("very optimistic/440ppm" 500 MW plant, oxy-fuel CCS, 200km of pipeline and storage in an 800m aquifer) and 2050 worst-case ("pessimistic/business-as-usual" 500 MW plant, post combustion CCS, 400km of pipeline and storage in a 2500 m depleted gas field).
- **2070**: NEEDS 2050 best-case ("very optimistic/440ppm" 500 MW plant, oxy-fuel CCS, 200km of pipeline and storage in an 800m aquifer)

9.2.3 Social assumptions

The data sources and assumptions for employment, human health impacts, large accident risks and intergenerational equity in future time periods are discussed below. As is the case in Chapters 4-8, indicators addressing local community impacts and human rights and corruption are not quantified as they are company-specific and cannot be assessed at the generic technology level. The amount of fossil fuel avoided is assumed constant over time in order to illustrate the fuel avoided relative to the present-day fossil fuel generation mix. The present-day values for the diversity of fuel supply for each technology (given in Sections 4.4.3.5, 5.4.3.5, 6.4.3.5, 7.4.3.5 and 8.4.3.5) are also constant over time as fuel supply mixes cannot be predicted. The results of this indicator therefore illustrate the improvement or deterioration in overall energy security relative to the present, assuming supply mixes are not altered.

All other data are assumed constant as they will not change in the future. The complete dataset of social impacts up to 2070 is given in Appendix 7.

9.2.3.1 Provision of employment

As is the case for environmental characteristics, future employment levels for nuclear, gas and coal power are assumed to be the same as present-day estimates to reflect their technological maturity. Given the lack of operational data, coal CCS is based on the standard coal dataset, but with adjustments to reflect its increased complexity in terms of fuel and material requirements:

employment in the coal mining stage is assumed to be 25% higher than non-CCS coal power due to the higher fuel use incurred by operating the CCS equipment (typically, this ‘energy penalty’ is approximately 16-31% with the bottom of the range corresponding to natural gas CCS plants [359]); employment at all other stages is assumed to be 10% higher than the equivalent stage in the non-CCS coal life cycle due to the higher number of components and amount of material added by the CCS equipment. Due to a lack of sufficient data, this 10% estimate is highly uncertain. However, as discussed in Section 6.4.3.1, over two thirds of employment in the coal life cycle is in coal mining, meaning inaccuracy in other stages is less influential.

Changes to coal CCS employment through time are then accounted for using the learning rates discussed in Section 9.2.1 and Appendix 6 (3.5-4.9%). The same technique is used for offshore wind and solar PV employment in future time periods: the present-day results discussed in Sections 7.3.3.1 and 8.3.3.1, respectively, are decreased through time using the learning rates discussed in Section 9.2.1 and Appendix 6 (12% for offshore wind, 18% for solar PV).

9.2.3.2 Human health impacts

Worker injuries

Worker injury estimates for each technology are calculated using the employment result for the appropriate year, using the method described in Section 3.2.3.2. However, injury rates for each industrial sector are projected out to 2070 by extrapolating the trend observed in nine years of historical data from the Health and Safety Executive (2001-2010, [151]) and Safe Work Australia (1999-2008, [220]). Given a lack of further data, injury rate reductions were simply linearly extrapolated, resulting in future rates that are likely too low. This is particularly true for sectors with impressive recent safety gains such as ‘other mining’ (see Table 42) which consequently have very low injury rates by 2050. However, this is a novel area of work, and further study would be needed to improve accuracy. Rates beyond 2050 are assumed to stay approximately level as they reach the limits of what is practically achievable. The resulting sector-specific injury rates are as follows:

Table 42: Future worker injury rates by sector

				Projected future number of injuries (per 100,000 workers)		
Source	**Sector**	Present-day injury rate (per 100,000 workers)	9 year average historical rate of improvement (%/year)	***2020***	***2035***	***2050***[a]
Safe Work Australia [220]	Metal ore mining	1,485	5.90	723.0	290.4	116.6
	Coal mining	3,160	5.30	1,477.7	653.1	288.6
HSE [151]	Other mining	859.6	10.87	253.9	45.2	8.0
	Extractive and utility supply (total)	1,117.1	6.30	537.8	202.5	76.3
	Construction (total)	777.2	5.36	424.1	185.6	81.2
	Manufacturing (total)	811.8	5.09	457.9	209.3	95.6
	Manufacturing: Coke, Refined Petroleum Products & Nuclear Fuel	356.8	5.35	199.7	87.5	38.3
	Manufacturing – chemical and chemical products	675.3	4.51	404.9	202.6	101.4
	Electricity, gas, steam and hot water supply (total)	553.8	2.28	376.6	266.6	188.7

[a] Same figures are assumed for 2070

<u>Human toxicity potential & Human health impacts from radiation</u>

These two impacts are estimated as part of the LCA modelling discussed above (Section 9.2.2).

9.2.3.3 Large accident risk

Large accident fatalities are based on estimates by the Paul Scherrer Institut [221] addressing each technology in future time periods. Estimates are not available beyond 2050, so the 2050 data are also used for 2070.

9.2.3.4 Intergenerational equity

<u>Abiotic resources (elements and fossil fuels)</u>

These indicators are calculated via LCA modelling, therefore the same assumptions outlined in Section 9.2.2 apply.

Volume of liquid CO_2 for storage

Direct CO_2 emissions from coal CCS are calculated based on non-CCS coal plants emitting an average of 702 g CO_2/kWh in the operational stage (as in the NEEDS project from which LCA data are taken [360]). This has been adjusted with an energy penalty of 25% due to the operation of the CCS equipment, in line with the assumptions for employment data (Section 9.2.3.1). Total emissions are therefore approximately 880 g CO_2/kWh. The capture rate for this emitted CO_2 is assumed to be 90% (as in the NEEDS project [360]),resulting in 790 g CO_2/kWh being captured. For storage, an injection pressure of 110 bar is assumed, as in Leman, the biggest UK gas field being considered for CO_2 storage [295].

9.3 Definition of future scenarios for the UK electricity mix

The future of energy is highly uncertain because technological innovation is not predictable, meaning factors such as cost, demand and the availability of technologies cannot be projected accurately into the future. New technological possibilities may have profound effects on the ways in which we produce or consume energy. Alternatively, they may not, and this cannot be known in advance. However, despite this unpredictability, it is also true that energy requires an element of long-term planning due to the long times taken to develop, license, build and operate power plants and their requisite infrastructure. In addition, carbon emission reduction has become a central theme of energy policy, itself requiring consideration of emissions well into the future (as CO_2 is a cumulative problem rather than an acute one). To help address this dilemma, scenario analysis can be used to consider a range of future possibilities and aid long-term planning. This does not attempt to predict, rather it explores possible futures. Typically the outputs of scenarios are qualitative and quantitative descriptions of the transition from the current situation to some future state, usually considering a time line of a few decades. Examples of energy scenario analysis include work by the IEA [361] and, in the UK, the Tyndall Centre [89], UK Energy Research Centre (UKERC) [3], as well as the Government itself [29].

In this work, three main scenarios (‘65%’, ‘80%’ and ‘100%’) are considered, each with either one or two sub-scenarios, depicting possible futures of electricity in the UK to 2070. All the scenarios are driven by the need to reduce CO_2 emissions, as this is one of the main policy drivers in the UK [28, 29]. The scenarios explore different CO_2 reduction levels for electricity, ranging from 65% to 100% decarbonisation of the electricity mix by 2050 (note that this refers to the direct emissions of CO_2 from combustion in power plants rather than the life cycle emissions). The narratives for scenarios 65% and 100% are based on those developed by UKERC [3] and Tyndall [87] but have been developed further to focus on electricity (as opposed to the original scenarios which considered the whole UK energy system). In addition, a new scenario (80%) was developed as part of this research. The scenarios are summarised in Table 43 and described in more detail below, together with the sub-scenarios. They are also differentiated in terms of their carbon emission pathways in Figure 41.

Table 43: Summary of scenarios considered in this analysis (all changes relative to 1990 levels)

65%	• Based on UKERC 'Faint-heart' scenario [3]: limited action is taken to prevent climate change. • Total (direct) UK CO_2 emissions reduce by 24% (including international aviation and shipping) by 2070. • Electricity is significantly decarbonised, with emissions reduced by 65% by 2050 and 80% by 2070. • Electricity demand increases slowly, increasing by 50% by 2070.
80%	• Decarbonisation of electricity is intermediate between scenarios '65%' and '100%', reaching 80% reduction by 2050 (in line with Government targets for the whole economy) and eventually 98% by 2070. • Follows the same electricity demand profile as the 100% scenario.
100%	• Based on UKERC 'Carbon Ambition' scenario, with carbon emissions in line with the carbon budgets set by the Committee on Climate Change [362]. • Total UK CO_2 emissions reduce by 80% (including international aviation and shipping) by 2070. • Carbon emissions from electricity are effectively zero by 2050. • Total energy demand reduces by 30% by 2070, but electricity demand increases by 60% as transport and other services switch to electricity (demand peaks in 2050 at 78% higher than 1990, then declines to 60% with efficiency improvements)

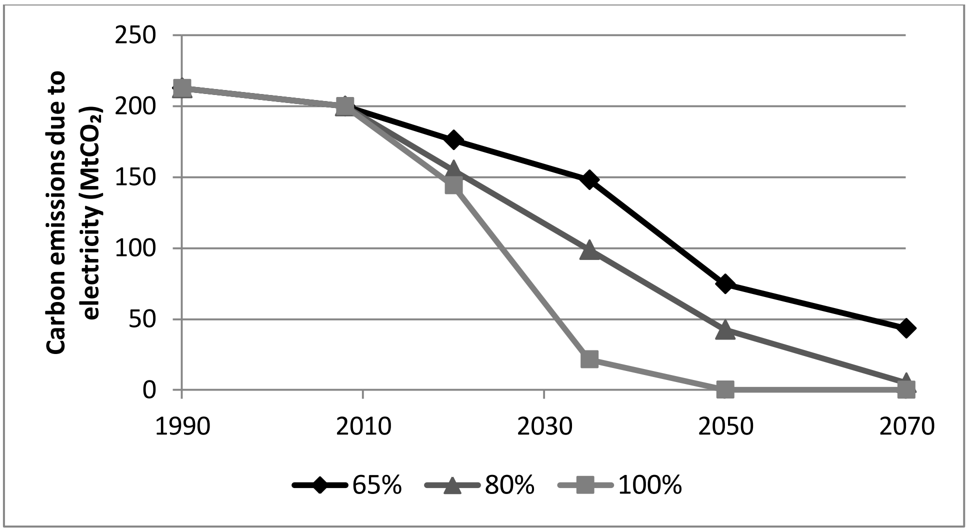

Figure 41: Pathways for reduction of direct CO_2 emissions from UK electricity for scenarios 65%, 80% and 100%

9.3.1 Scenario 65%

Scenario 65% reflects a future in which limited action is taken to prevent climate change. Carbon emissions from the economy as a whole reduce by just 15% by 2050 compared to 1990. By 2070, the reduction reaches 24%. This means that the UK misses, by a large margin, its legally binding requirement to reduce CO_2 emissions by 80% by 2050 [9]. The majority of the emissions reduction achieved in this scenario is due to the electricity sector, which decarbonises by 65% by 2050 and 80% by 2070.

Two potential electricity mixes have been investigated within this scenario, 65%-1 and 65%-2, each conforming to the scenario's electricity demand requirements and carbon constraints. The mixes are given in Table 44 together with the electricity demand in each year and the 2009 electricity generation mix adjusted to include only modelled technologies as discussed in Section 9.1.1.4. The description and justification for each sub-scenario are given in the sections below.

Table 44: Potential electricity mixes in Scenario 65%

	Electricity generation (GWh)	Carbon constraint for electricity ($MtCO_2$/yr)	Mix 65%-1	Mix 65%-2
2009	375,663	n/a	Coal: 30.4% Gas (CCGT): 46.8% Nuclear (PWR): 20.1% Wind (offshore): 2.7% Solar (PV): 0.01% Coal (CCS): 0%	
2020	336,375	176.1	Coal: 33% Gas (CCGT): 54% Nuclear (PWR): 8.1% Wind (offshore): 4% Solar (PV): 0.9% Coal (CCS): 0%	Coal: 32% Gas (CCGT): 52.8% Nuclear (PWR): 11.66% Wind (offshore): 3% Solar (PV): 0.5% Coal (CCS): 0%
2035	376,729	148.0	Coal: 21% Gas (CCGT): 49.6% Nuclear (PWR): 2.4% Wind (offshore): 10% Solar (PV): 2% Coal (CCS): 15%	Coal: 25% Gas (CCGT): 39.3% Nuclear (PWR): 18.2% Wind (offshore): 6% Solar (PV): 1.5% Coal (CCS): 10%
2050	407,855	74.6	Coal: 4% Gas (CCGT): 33% Nuclear (PWR): 2.2% Wind (offshore): 16.8% Solar (PV): 3% Coal (CCS): 41%	Coal: 12% Gas (CCGT): 23% Nuclear (PWR): 28.5% Wind (offshore): 11.5% Solar (PV): 3% Coal (CCS): 22%
2070	455,539	43.4	Coal: 2% Gas (CCGT): 11% Nuclear (PWR): 0% Wind (offshore): 24% Solar (PV): 8% Coal (CCS): 55%	Coal: 4% Gas (CCGT): 15% Nuclear (PWR): 30.1% Wind (offshore): 20.9% Solar (PV): 8% Coal (CCS): 22%

9.3.1.1 Electricity mix 65%-1

The electricity mix in 65%-1 up to 2070 is shown in Figure 42.

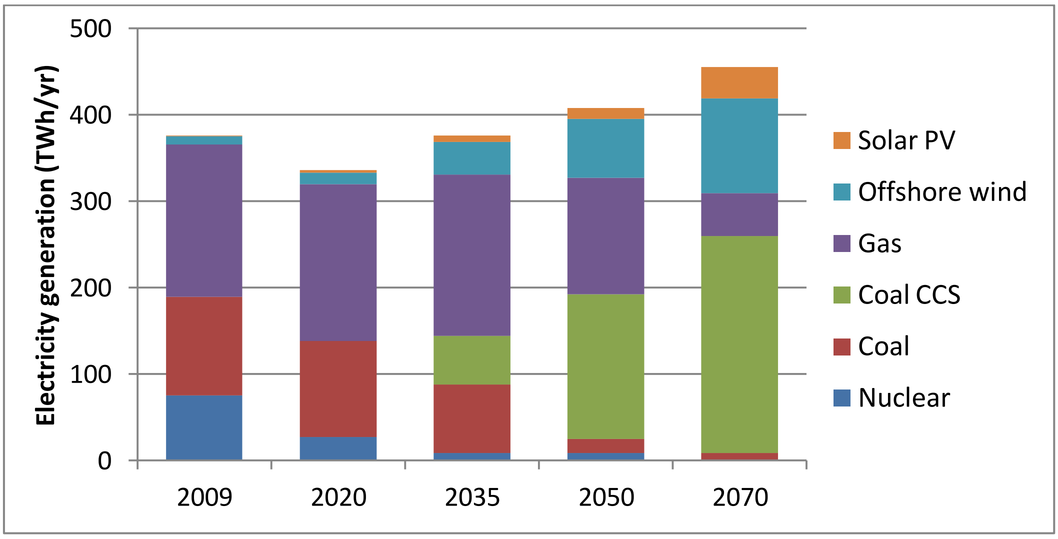

Figure 42: Electricity generation mix through time for Sub-scenario 65%-1

This sub-scenario illustrates a future in which carbon capture and storage (CCS) technologies become commercially successful, but new nuclear build does not occur, perhaps as a result of political opposition or economic difficulties. Under the 65% scenario, carbon constraints are not particularly tight, meaning coal and gas continue to play a role well into the future, together contributing 13% of electricity even in 2070 (see Figure 42). In fact, it is assumed that the UK withdraws from the EU Large Combustion Plant Directive (LCPD), which would otherwise reduce output from coal by 2016 [7]. It is not clear what, if any, penalty the UK would incur by withdrawing from the LCPD. In this sub-scenario, coal CCS delivers the majority of the carbon savings, although solar PV and wind also experience steady growth.

In 65%-1, current nuclear power plants shut down according to their commercial schedule, with Sizewell B being granted a life extension of 20 years as anticipated [363]. No further plants are added.

It is assumed that coal CCS is not viable until after 2020 (apart, perhaps, from demonstration plants of negligible capacity). However, approximately 10 GW[37] of coal CCS would then be

[37] Installed capacities given here are estimated using approximate present-day capacity factors: coal = 62%, gas = 62%, nuclear = 85%, wind = 30-35% (depending on duration from the present day, as improvements are expected) and solar = 9%. The capacity factor of coal CCS is assumed to be the same as that of coal.

installed between 2020 and 2035, 20 GW between 2035 and 2050 and a further 15 GW before 2070. This growth rate correlates well with the 'core MARKAL' scenario in the Government's Carbon Plan [29], which anticipates 28 GW of CCS capacity by 2050 (cf. 30 GW here).

Expansion of renewables in 65%-1 is considerable, but less than presently anticipated. For instance, planned offshore wind capacity could exceed 33 GW in the next 10-15 years [364], but that level is not reached until the 2060s in 65%-1, perhaps as a result of reduction or withdrawal of government support. Likewise, growth of solar PV is far lower than its current rate of 50-90 MW/month [365], with an average rate of 30-40 MW/month until post-2050, at which point deployment accelerates to around 125 MW/month.

9.3.1.2 Electricity mix 65%-2

The progression of the electricity mix in 65%-2 is shown below in Figure 43.

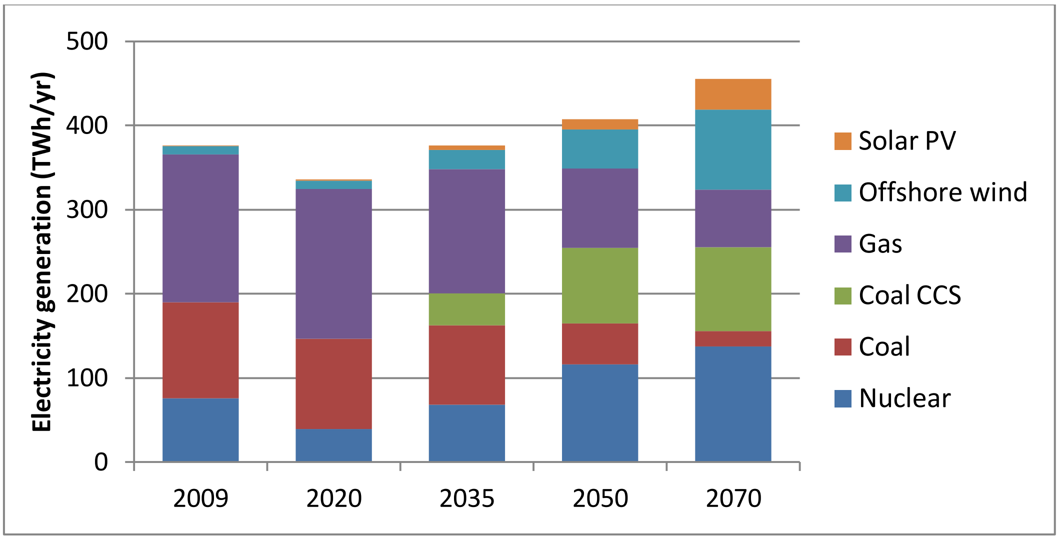

Figure 43: Electricity generation mix through time for Sub-scenario 65%-2

Sub-scenario 65%-2 is similar to 65%-1, but with the assumption that nuclear new build goes ahead as well as coal CCS (see Figure 43). Since, in contrast with 65%-1, both of these technologies are available, the required installed capacity can be reached with quite low build rates of each: nuclear capacity in 2070 is only around 18 GW, while coal CCS is also approximately 18 GW. An amount of load-following is expected with CCS plants whereas nuclear plants are mainly expected to provide baseload, hence the total output of coal CCS is lower than that of nuclear despite installed capacity being the same. In terms of new nuclear, it is assumed that around 1.6 GW comes online by 2020 (equivalent to one Areva EPR [20]) , followed by a further

6.4 GW by 2035, another 6.4 GW by 2050 and finally 4 GW by 2070. The peak growth rate is therefore around 0.4 GW/year: far lower than the historical maximum of 4.5 GW/year (in France from 1979-88) and sitting at the bottom end of the possible range suggested by the Carbon Plan [29]. Thus, the required build rates of both coal CCS and nuclear plants should be easily achievable.

Output from gas plants gradually declines as installed capacity is replaced with coal CCS and nuclear power due to their lower CO_2 emissions. Expansion of solar PV in Scenario 65%-2 is identical to that in Scenario 65%-1. Offshore wind, however, expands slightly more slowly, having an installed capacity of about 30 GW in 2070 (compared to ~35 GW in 65%-1) due to less capacity being necessary as a result of new nuclear build (which has lower assumed costs as is therefore installed preferentially).

9.3.2 Scenario 80%

Scenario 80% provides a steady decarbonisation path for the electricity sector that achieves the Government's stated aim of 80% carbon reduction by 2050 [29]. The scenario assumes, therefore, that other sectors reduce their emissions by similar percentages. This is contrary to the approach taken in scenario 100% and in the Carbon Plan, in which electricity brings about the majority of UK emissions reductions, becoming virtually zero carbon by 2050 (see Section 9.3.3). Annual electricity demand steadily increases as more services are electrified, finally beginning to decline post-2050 as efficiency improvements outpace demand increases.

One illustrative electricity mix has been investigated within this scenario. It is shown in Table 45 together with the electricity demand in each year and the 2009 electricity generation mix adjusted to include only modelled technologies as discussed earlier in Section 9.1.1.4.

Table 45: Potential electricity mix for Scenario 80%

	Electricity generation (GWh)	Carbon constraint for electricity ($MtCO_2$ /yr)	Mix 80%
2009	375,663	n/a	Coal: 30.4% Gas (CCGT): 46.8% Nuclear (PWR): 20.1% Wind (offshore): 2.7% Solar (PV): 0.01% Coal (CCS): 0%
2020	352,339	155.0	Coal: 24% Gas (CCGT): 54.5% Nuclear (PWR): 11.1% Wind (offshore): 9% Solar (PV): 1.4% Coal (CCS): 0%
2035	383,940	98.8	Coal: 14.6% Gas (CCGT): 30% Nuclear (PWR): 26.4% Wind (offshore): 18% Solar (PV): 3% Coal (CCS): 8%
2050	535,115	42.5	Coal: 4% Gas (CCGT): 12% Nuclear (PWR): 34% Wind (offshore): 30% Solar (PV): 10% Coal (CCS): 10%
2070	483,676	5.1	Coal: 0% Gas (CCGT): 0.5% Nuclear (PWR): 35.7% Wind (offshore): 33.8% Solar (PV): 19% Coal (CCS): 11%

9.3.2.1 Electricity mix 80%

The assumed progression of the electricity mix over time in Scenario 80% is shown in Figure 44.

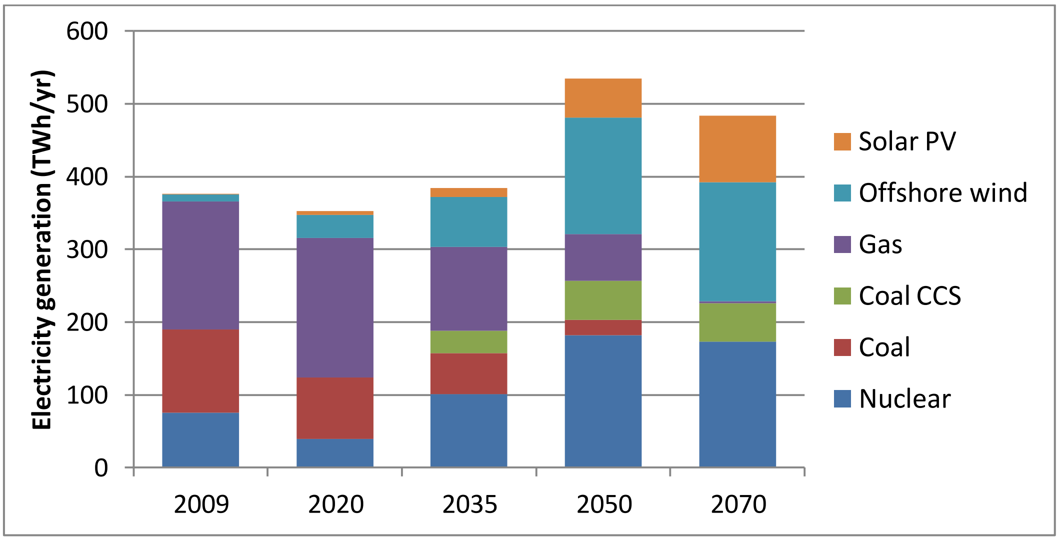

Figure 44: Electricity generation mix through time for Scenario 80%

This scenario assumes a future energy mix that includes both new nuclear and coal with CCS. Renewables continue to increase their grid penetration at a steady rate, resulting in an electricity mix that is quite evenly balanced between fossil, nuclear and renewable sources until after 2050 when renewables begin to dominate (see Figure 44). Thus, growth rates required for individual technologies are modest. Nuclear power, for example, experiences 1.6 GW of new build by 2020, followed by approximately 11 GW by 2035 and a further 11 GW by 2050, after which new build ceases. As in the other scenarios and sub-scenarios, currently operating nuclear power plants shut down according to their commercial schedule, with Sizewell B being granted a life extension of 20 years as anticipated [363]. Offshore wind has a total installed capacity of approximately 22 GW by 2035, which is considerably less than the currently planned capacity of over 33 GW [364]. By 2070, however, this has increased to around 50 GW. Solar PV experiences expansion at current rates until after 2035, at which point installation accelerates, culminating in a total capacity of around 115 GW by 2070. This is equivalent to about 39 million residential installations at current sizes, although this number would likely decrease as PV efficiency improves allowing higher capacities to be installed per unit area.

In comparison to scenarios in the Carbon Plan, this electricity mix is most similar to "Higher renewables; more energy efficiency", requiring similar installed capacities of nuclear (23 c.f. 16 GW), CCS (10 c.f. 13 GW) and renewables (120 c.f. 106 GW) in 2050 [29].

The carbon targets in Scenario 80% allow a relatively modest rate of expansion of variable-output renewables as well as retention of some fossil capacity well into the future. Thus, the energy storage and demand-side management (‘smart grid’ features) that will be required to accommodate a large capacity of renewables are likely to be relatively minimal until 2050 or later. However, as noted in Section 7.4.1.1, the consequences of grid variability are very much an ongoing area of research.

9.3.3 Scenario 100%

Scenario 100% describes a future in which the UK’s national carbon target of 80% reduction by 2050 is met via a combination of low-carbon technologies and efficiency improvements that allow reductions in demand. The carbon pathway for the economy as a whole follows closely the carbon budgets set out by the Committee on Climate Change [362]. The scenario also operates on the widely accepted principle that an effective way to reduce carbon emissions is to transfer traditionally fossil-fuelled services (such as transport and heating) to electricity, on the basis that electricity is easier to decarbonise than other energy forms. This approach is also taken in the Carbon Plan, and similarly requires electricity to be virtually zero-carbon (at the point of generation) by 2050 [29]. Another consequence of this is that electricity demand increases greatly, although this is partly offset by efficiency improvements.

Two potential electricity mixes have been investigated within this scenario, each meeting its defined electricity demand and carbon constraints. The mixes are given in Table 46 together with the electricity demand in each year and the 2009 electricity generation mix adjusted to include only modelled technologies as discussed earlier in Section 9.1.1.4.

Table 46: Potential electricity mixes in Scenario 100%

	Electricity generation (GWh)	Carbon constraint for electricity ($MtCO_2$/yr)	Mix 100%-1	Mix 100%-2
2009	375,663	n/a	Coal: 30.4% Gas (CCGT): 46.8% Nuclear (PWR): 20.1% Wind (offshore): 2.7% Solar (PV): 0.01% Coal (CCS): 0%	
2020	352,339	144.1	Coal: 23% Gas (CCGT): 53% Nuclear (PWR): 7.8% Wind (offshore): 11.8% Solar (PV): 1.4% Coal (CCS): 3%	Coal: 23% Gas (CCGT): 49.6% Nuclear (PWR): 14.5% Wind (offshore): 8.5% Solar (PV): 1.4% Coal (CCS): 3%
2035	383,940	21.6	Coal: 0% Gas (CCGT): 9% Nuclear (PWR): 2.3% Wind (offshore): 43% Solar (PV): 21.7% Coal (CCS): 24%	Coal: 0% Gas (CCGT): 13% Nuclear (PWR): 42.1% Wind (offshore): 29% Solar (PV): 7.9% Coal (CCS): 8%
2050	535,115	0.214	Coal: 0% Gas (CCGT): 0% Nuclear (PWR): 1.7% Wind (offshore): 45.3% Solar (PV): 52.6% Coal (CCS): 0.4%	Coal: 0% Gas (CCGT): 0% Nuclear (PWR): 46.9% Wind (offshore): 37.2% Solar (PV): 15.5% Coal (CCS): 0.4%
2070	483,676	0.108	Coal: 0% Gas (CCGT): 0% Nuclear (PWR): 0% Wind (offshore): 45% Solar (PV): 54.8% Coal (CCS): 0.2%	Coal: 0% Gas (CCGT): 0% Nuclear (PWR): 50.1% Wind (offshore): 30.7% Solar (PV): 19% Coal (CCS): 0.2%

9.3.3.1 Electricity mix 100%-1

The progression of the electricity mix in 100%-1 is shown below in Figure 45.

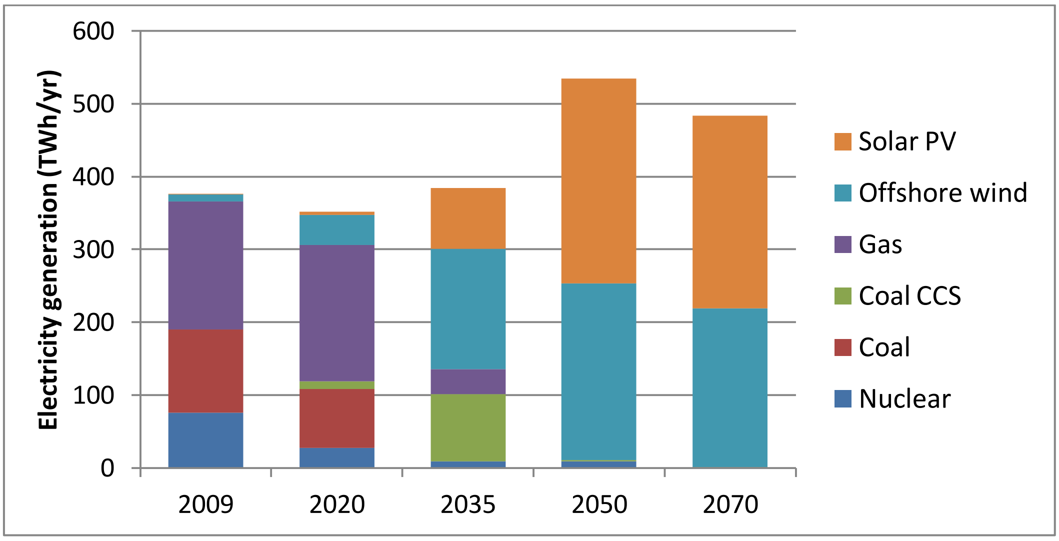

Figure 45: Electricity generation mix through time for sub-scenario 100%-1

This sub-scenario describes a future in which new nuclear build is not successful. Currently-operating nuclear power plants shut down according to their commercial schedule, with Sizewell B being granted a life extension of 20 years as anticipated [363].

Under the 100% scenario, carbon constraints are significant – with electricity effectively becoming zero-carbon by 2050 – meaning coal CCS cannot play a major role as it emits too much CO_2 despite its carbon capture technology. Consequently, use of coal CCS follows a fast roll-out period and an even faster period of retirement or mothballing. Use of coal CCS peaks by 2035, at which point it provides 24% of electricity, equivalent to around 17 GW capacity, virtually all of which must then come offline between 2035 and 2050 to meet the CO_2 targets. As a result, this sub-scenario relies almost entirely on renewables, which provide 98% of electricity (524 TWh) by 2050 (see Figure 45). Because of the limited number of renewable technologies considered in this work, this 524 TWh must come from wind and solar power, creating a situation which would be untenable without vast amounts of cheap energy storage. Moreover, it requires that solar and wind power expand to extreme levels: for instance, about 350 GW of solar PV capacity is needed by 2050, equivalent to over 100 million residential installations at typical current sizes. This is more than four times the current number of households in the UK [366]. Similarly, the installed capacity of wind turbines in 2050 is equivalent to around 16,000 of the largest models currently available. For these reasons, this sub-scenario is probably unrealistic. Nevertheless, it is still considered here as an extreme case to explore the possible sustainability implications. Furthermore, the 524 TWh could also come from other sources such as wave, tidal and, crucially for load-following, biomass. As already explained, it was not possible to consider all these technologies in this work, so assessing the sustainability implications of such a mix could be a topic of future work.

9.3.3.2 Electricity mix 100%-2

The electricity mix over time for 100%-2 is shown in Figure 46.

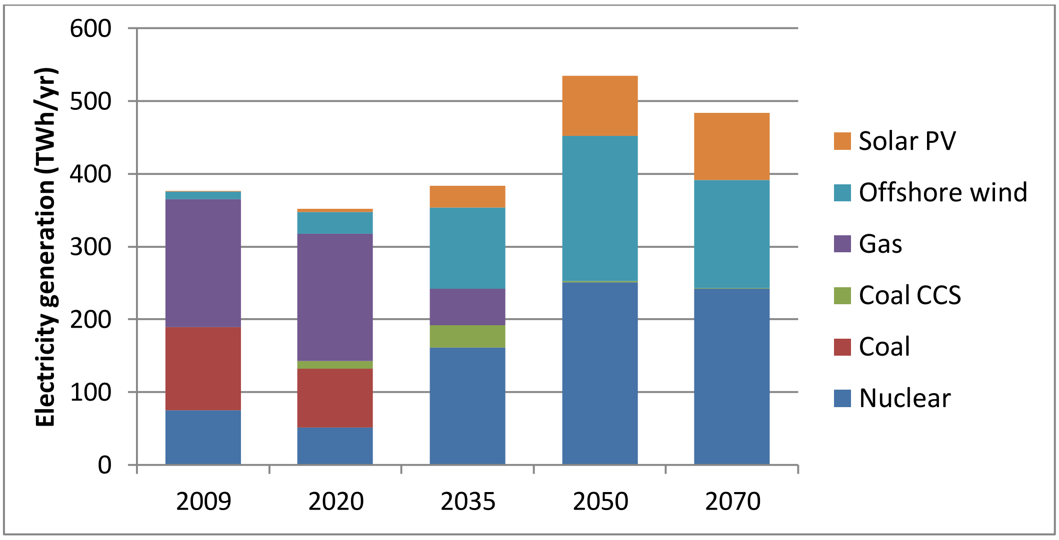

Figure 46: Electricity generation mix through time for sub-scenario 100%-2

This sub-scenario illustrates a future in which both new nuclear and coal with carbon capture and storage become a commercial reality. As in 100%-1, aggressive carbon constraints mean that coal CCS cannot play a major role. As a result, nuclear power is assumed to dominate the market, ultimately providing 50% of electricity by 2070 (see Figure 46). Nuclear growth rates are therefore ambitious, albeit realistically so: 3.2 GW come online by 2020 (equivalent to the twin EPR plant proposed at Hinkley Point by EDF Energy [363]), followed by another 17.3 GW by 2035 and a further 12 GW by 2050, after which no more new nuclear capacity is required as efficiency improvements decrease electricity demand. Thus, the maximum build rate is around 1.2 GW/year between 2020 and 2035, which is easily within the range suggested by the Carbon Plan [29]. The recently published UK Nuclear Fission Technology Roadmap also exceeds the demands of this scenario, with about 7.5 GW extra nuclear (LWR) capacity by 2050 in its 'expansion' scenario (40 vs 32.5 GW) [367].

As in the other scenarios and sub-scenarios, currently operating nuclear power plants shut down according to their commercial schedule, with Sizewell B being granted a life extension of 20 years as anticipated [363].

It is assumed that around 2 GW of coal CCS is installed by 2020, providing 3% of electricity. This increases to 8% by 2035, but then rapidly declines in order to meet carbon targets: by 2050, coal CCS cannot generate more than 0.4% of electricity, meaning installed capacity has to decline from over 5 GW in 2035 to around 400 MW in 2050. This is less than even the least CCS-intensive scenario in the Carbon Plan ('Higher nuclear; less energy efficiency'), which assumes 2 GW in 2050 [29].

Solar installation continues at a pace similar to today's until 2020, after which it accelerates, eventually providing 19% of electricity in 2070. This represents an installed capacity of approximately 115 GW, equivalent to around 38 million residential installations at today's typical sizes (although as mentioned previously, PV efficiency gains will allow greater capacity per unit area, reducing the number of installations required). Expansion of wind power is also ambitious, peaking in 2050 at 37.2% of electricity generated, representing an installed capacity of over 60 GW. However, given current plans to build 33 GW in the next 10-15 years [364], that level seems reasonable. Clearly, with such high penetration of renewables, significant energy storage and demand-side management would be needed. However, as is the case for scenario 100%-1, in reality some of the 282 TWh produced by renewables in 2050 could come from other sources not considered here, such as wave, tidal and, biomass; these technologies, particularly biomass, would reduce the need for energy storage and demand side management (to an extent). Further work focusing on these technologies would prove useful.

The following sections present and discuss the results of the sustainability assessment of the different scenarios.

9.4 Sustainability assessment of future UK electricity scenarios

This section presents the results of the scenarios described in Section 9.3 using the data discussed in Section 9.2 and given in Appendix 7. This section only compares the final year of each sub-scenario (2070) to the present with reference to other years where necessary. The results for 2020, 2035, 2050 and 2070 can be found in Appendix 8.

The same data have been used to develop the Scenario Sustainability Assessment Tool (SSAT) as part of this PhD: the tool is available on the attached CD. SSAT allows users to define their own future scenarios and electricity mixes and compare their sustainability impacts using the indicators developed in this work. Guidance on the use of SSAT is also attached on CD. It should be noted that users may base their electricity mixes on four predefined scenarios, including the ‘65%’ and ‘100%’ scenarios considered here. However, as SSAT was developed as part of the SPRIng project, the scenario names correspond to those of SPRIng [see 87]. Thus, 65% is named A; 100% is named B.

9.4.1 Techno-economic results

This sub-section addresses the techno-economic results of the scenario analysis for the year 2070, with the 2009 electricity mix included for comparison. The summary results are presented in Figure 47 (per year) and Figure 48 (per unit of electricity generated) and are discussed below.

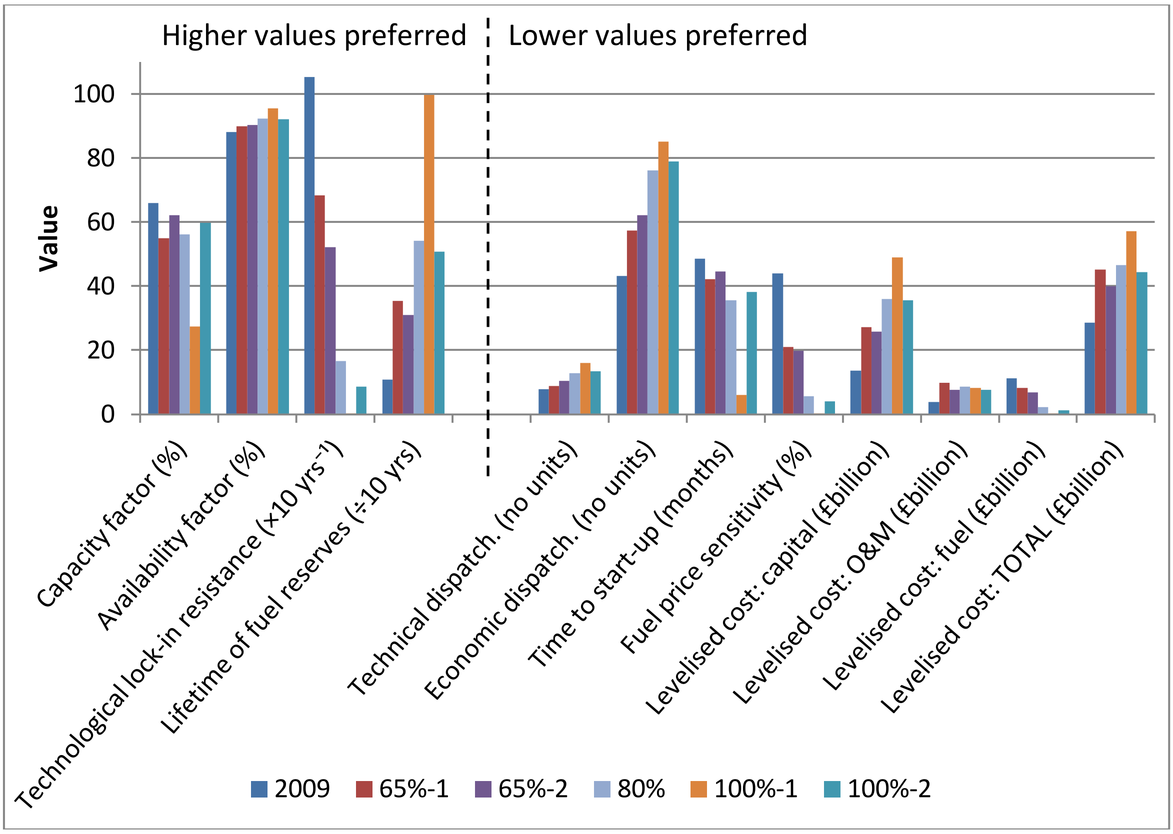

Figure 47: Techno-economic comparison of potential future electricity mixes for the UK, expressed per year. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. For full results, see Appendix 8.

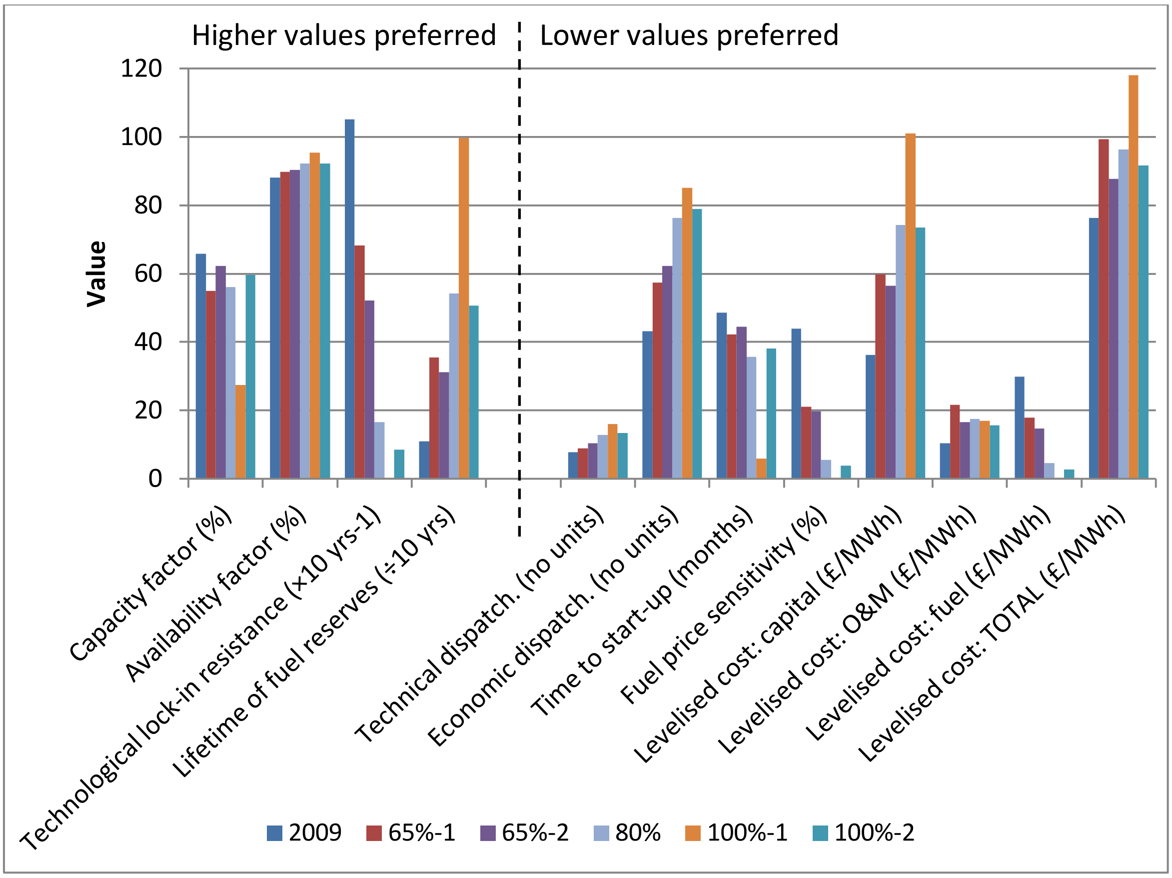

Figure 48: Techno-economic comparison of potential future electricity mixes for the UK, expressed per unit of electricity generated. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. For full results, see Appendix 8**.**

9.4.1.1 Operability

Capacity and availability factors

As shown in Figure 47, the total system capacity factor of all future scenarios is lower than that of the present day. This is due to the increased adoption of renewables which, being variable in output, have low capacity factors. This is particularly apparent in sub-scenario 100%-1 which, by 2070, derives virtually all (99.8%) of its electricity from renewables. As a result, it has the lowest capacity factor of the scenarios, at 27% compared to 66% in 2009. Availability factors show the opposite trend: increased renewable penetration brings higher values, increasing from 88% in the present to 95% in 2070 in the highest case (100%-1). This means slightly fewer unscheduled production outages would be expected in future, particularly in 100%-1. However, this does not necessarily mean that supply to consumers would be more reliable: such high levels of renewables mean output would be highly variable and grid management would be far beyond what is currently achievable, necessitating widespread energy storage. This would of course increase the cost of electricity to consumers, but the extent of this increase is not currently known (and therefore is not considered here).

Technical and economic dispatchability

In all scenarios, dispatchability of the electricity mix as a whole is lower than in the present. Scenario 100%-1 is the worst in this respect, with technical dispatchability in 2070 of 16.0 compared to 8.8 in 2009, and economic dispatchability in 2070 of 85 relative to 43 in the present (lower scores being preferable in both cases). This is because the most dispatchable technologies of those assessed are coal and gas power, both having relatively low capital costs and high load-following ability (see Sections 5.4.1.1 and 6.4.1.1). As carbon targets force nuclear and renewables to replace fossil plants, it thus becomes more difficult to match supply to demand.

Wind and solar power in particular are inherently non-dispatchable as output cannot be controlled. Nuclear power, on the other hand, is capable of following load to an extent, but this depends on the price incentive: high electricity sale prices at times of peak demand would be necessary to incentivise nuclear plant owners to reduce output at other times (see Section 4.4.1.1). In scenarios such as 80% and 100%-2, high renewable penetration (and therefore variable output) might facilitate this. However, as discussed in Sections 0 and 9.3.3.2, an extremely large capacity of energy storage and load-following biomass plants would be necessary to make sub-scenarios 100%-1 and 100%-2 feasible. The sustainability impacts of this are unknown and are beyond the scope of this study, warranting further research.

Lifetime of global fuel reserves

The effective life of fuel reserves for electricity generation will clearly correlate positively with renewables because they are fuel-free and have infinite reserve lifetimes. This is seen in sub-scenario 100%-1 for which the result reaches about 1000 years (which is the artificial cap set on fuel lifetime for renewables to enable calculation). The result is much lower, at 507 years, in 100%-2 due to nuclear power providing 50% of electricity: at current consumption rates, identified economically exploitable uranium reserves will only last another 20 years by 2070 (to 2090). However, as discussed in Section 4.4.1.1, the lifetime of uranium reserves is very likely to increase substantially in future due to the relatively low level of exploration in recent decades and the increasing possibility of extraction from alternative sources such as phosphates[38] and, at

[38] Low concentrations of uranium occur in rock phosphate deposits (typically <200 ppm U). When phosphate is extracted, primarily for the fertiliser industry, this uranium remains in the product and is thus distributed throughout the environment wherever the product is applied. Extracting the uranium as a by-product therefore benefits the environment and human health as well as increasing uranium reserves. Estimates of the global reserves of uranium in phosphates range from 9 to 22 Mt U, compared to 5.4 Mt U of conventional uranium resources [368].

higher prices, sea water. If uranium from phosphates is included in the estimate, the uranium reserve lifetime increases by about 600 years [45], meaning the overall result for 100%-2 would come closer to that of 100%-1.

9.4.1.2 Technological lock-in resistance

Ratio of plant flexibility and operational lifetime

This indicator is an estimate of how well each option caters for potential changes in the way that energy is used nationally, accounting for whether power plants could be modified to tri-generate electricity, heating and cooling, to have negative global warming potential (e.g. integrated biomass and CCS) or to produce hydrogen at high temperatures. As shown in Figure 47 and Figure 48, all future scenarios are less resistant to technological lock-in than the present-day electricity mix. This is primarily due to the inability of solar, wind and nuclear power (at least in terms of PWRs) to provide these services, together with the long 60 year lifetime of nuclear plants. Thus lock-in resistance decreases from a score of 10.5 yrs^{-1} in 2009 to 0.02 yrs^{-1} in the worst case (100%-1).

9.4.1.3 Immediacy

Time to start up

Construction times are quite similar in all sub-scenarios apart from 100%-1 which is preferable in this respect due to its extreme use of solar power: solar installations are modular and, in the case of small systems, can normally be completed in 2-3 days, giving 100%-1 a score of 5.9 months in 2070 (compared to 48.6 months in 2009). Interest accrued during construction is therefore negligible and, from the system management perspective, installed capacity on the grid can be increased quickly according to changes in electricity demand (although high capital costs may prevent this).

9.4.1.4 Levelised cost of generation

Capital, operational, fuel and total costs

Figure 48 illustrates the trend towards capital-intensive technologies in all future scenarios. This is because low-carbon technologies tend to have high upfront costs and low operating costs: the levelised cost of nuclear power, for example, is 76% capital, while the corresponding figures for wind and solar are 75% and 94%, respectively. This means that future electricity mixes have lower marginal costs and are inherently less dispatchable, as discussed above. Moreover, it means that interest accrued during construction becomes a more important feature of economic viability in the future, as construction times will need to be as short and as fixed as possible to avoid significant cost overruns. This illustrates the importance of initiatives such as the Green Investment Bank which will specialise in lending to projects with higher perceived risks where high interest rates would otherwise inhibit development [369].

In terms of total cost, the results suggest that the costs of electricity will increase relative to the present in all cases, even taking into account technological learning rates. Of the scenarios in which carbon targets are met, 100%-2 is the cheapest option, being 20% more expensive than the current electricity mix per unit of electricity generated (9.2 pence/kWh c.f. 7.6). When nuclear power is excluded (as in 100%-1), total cost is 55% higher than the present at 11.8 pence/kWh. Scenario 100%-2 is comparable in terms of cost to 65%-1, 65%-2 and 80% despite having considerably lower carbon emissions. This is because nuclear power, the biggest energy source in 100%-2 by 2070, is expected to be cheaper than coal CCS in that time period.

It should be noted that the costs shown here exclude any system costs incurred due to increased energy storage requirements, balancing mechanisms and output restrictions that might be necessary in renewable-intensive scenarios. The magnitude of this extra cost is not currently known, but the topic is being assessed by National Grid [see, for instance, 324]. It is therefore likely that total costs will increase by more than the percentages estimated here, particularly in sub-scenarios 80% and 100%-1 which rely heavily on the variable output of wind power.

Additionally, it is important to bear in mind that electricity generation cost is not the same as cost to the consumer (i.e. the public): the latter is generally much higher. The difference reflects other costs incurred by utility companies, such as administration, research and development and network transmission fees. As a result, a 50% increase in generation cost would probably equate to an increase in electricity bills of less than 50%.

9.4.1.5 Cost variability

Fuel price sensitivity

In sub-scenarios 80%, 100%-1 and 100%-2, fuel price sensitivity is at least 87% lower than in today's energy mix. Even in 65%-1 and 65%-2, which rely more on fossil fuel generation, sensitivity is decreased to 21% and 20%, respectively, which compares to the 2009 value of 44%. As a result, electricity prices are less exposed to volatile international fuel markets, meaning prices paid by consumers should be more stable (despite being higher). This is primarily a result of decreased reliance on natural gas.

9.4.1.6 Financial incentives

Financial incentives and assistance

As stated in Section 9.2.1, financial incentives have not been quantified in this scenario analysis because future energy policy is unknown. However, future levelised cost estimates suggest that, by 2070, offshore wind and solar PV will be around 40% and 75% cheaper than today, respectively (see Appendix 6), meaning incentives should decrease in line with this and may not be necessary at all.

9.4.2 Environmental sustainability

This sub-section discusses the results of the environmental sustainability assessment of scenarios for the year 2070, with the 2009 electricity mix included for comparison. The results are discussed below and shown in Figure 49 (per year) and Figure 50 (per unit of electricity generated).

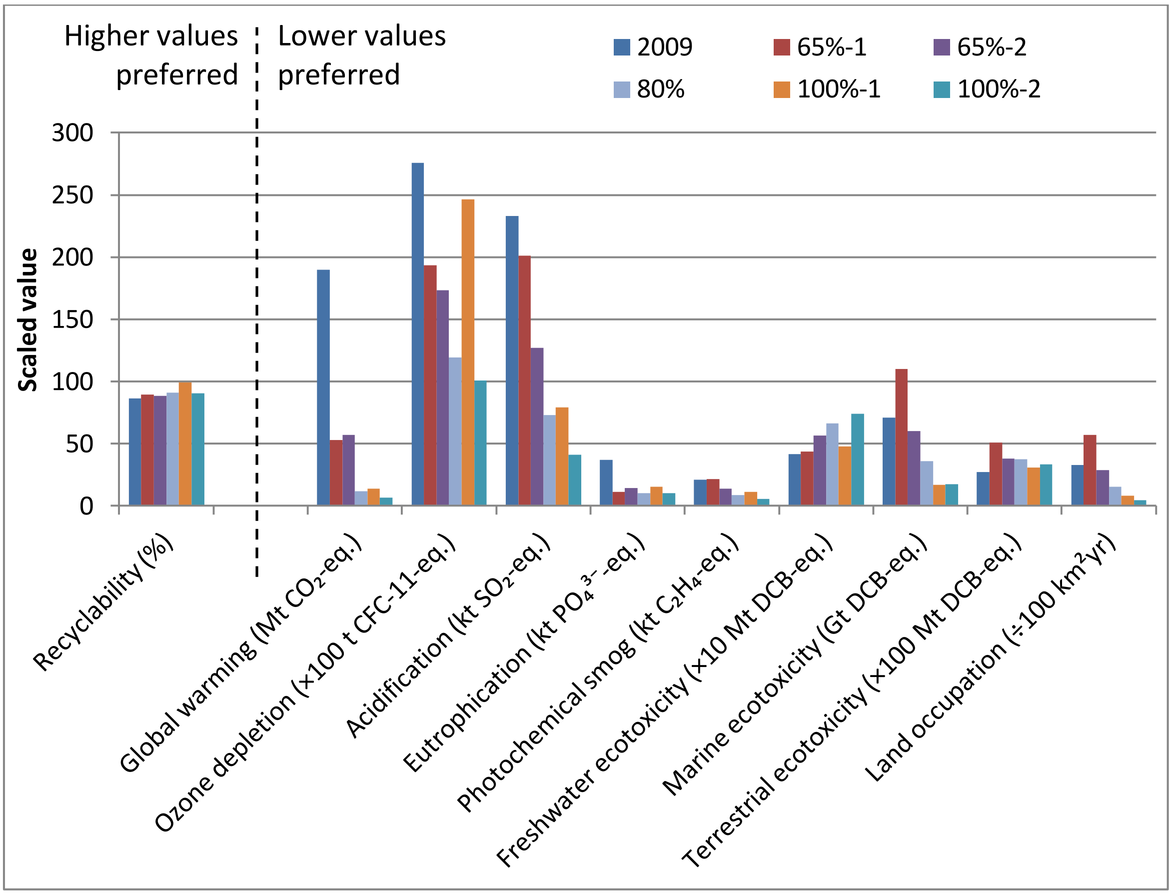

Figure 49: Environmental comparison of potential future electricity mixes for the UK, expressed per year. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. For full results, see Appendix 8.

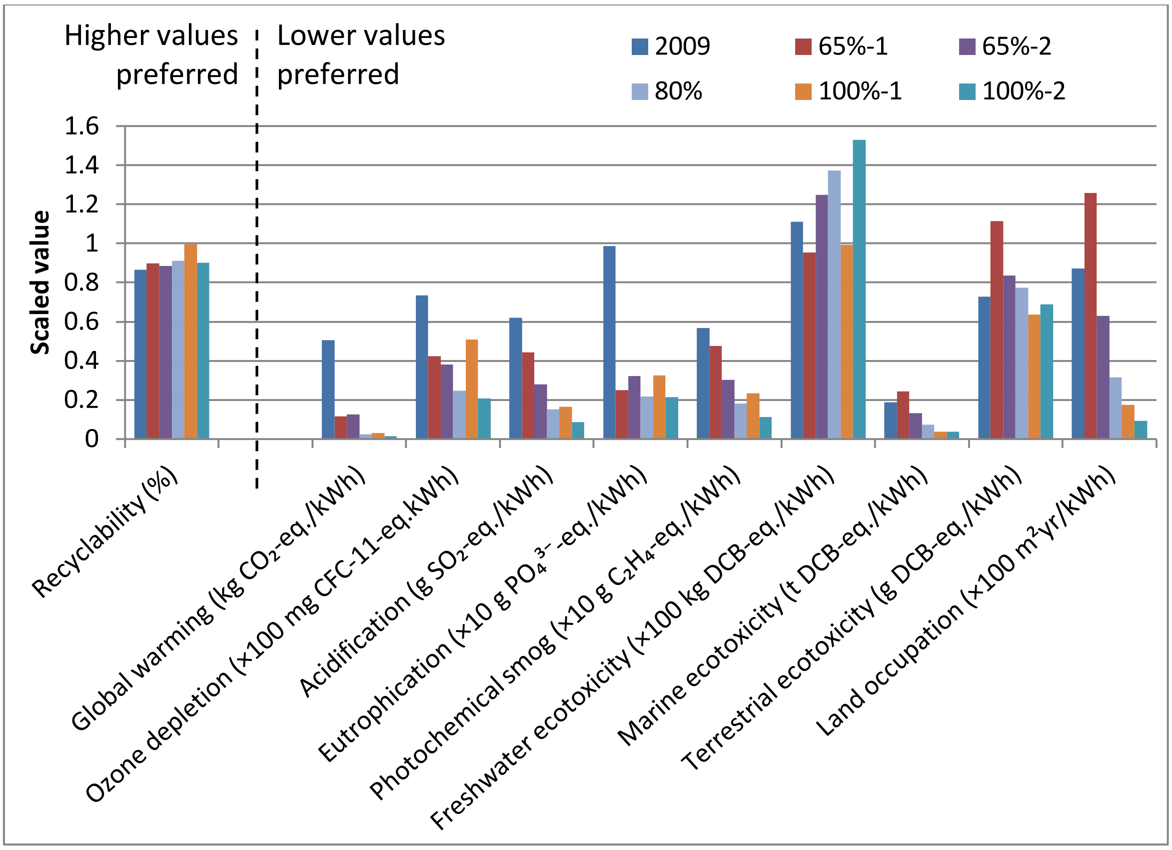

Figure 50: Environmental comparison of potential future electricity mixes for the UK, expressed per unit of electricity generated. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. For full results, see Appendix 8

9.4.2.1 Material recyclability

Recyclability of input materials

The average potential recycling rate of future electricity mixes is likely to be slightly higher than is the case today: in the scenarios assessed here, the rate of 86.4% in 2009 increases to 88.5-99.5% by 2070. This is mainly due to the increasing adoption of wind (99.4% recyclable) and solar PV (99.8% recyclable) systems and reflects the fact that renewable technologies tend to use proportionally more metal and less concrete, the latter currently being the main limiting factor in recyclability (as discussed in Section 3.2.2.1). However, as the present-day system is already 86% recyclable, improvements in future are likely to emerge mainly from improved national recycling rates rather than recyclability itself.

As discussed in Sections 7.4.2.1 and 8.4.2.1 (and shown in Appendix 3), the environmental impacts of wind and solar power are almost entirely due to the manufacturing stage, meaning recycling can dramatically improve all life cycle impacts (see Table 32 and Table 37). As a result, the benefit of end-of-life recycling increases as the electricity mix becomes more reliant on renewables.

9.4.2.2 Global warming potential (GWP)

As shown in Figure 49, the GWP of annual electricity production reduces markedly in all scenarios. From an estimated 190 Mt CO_2 eq. in 2009, by 2070 the total GWP has declined to a range of 6.8 Mt (in 100%-2) to 57 Mt (in 65%-2). The 100%-2 sub-scenario therefore represents a reduction of 96% over the present despite total electricity demand growing from 376 to 484 TWh per year. Per kilowatt-hour, even the least ambitious scenarios (65%-1 and 65%-2) represent a reduction of around 75% over the present-day value of 505 g CO_2 eq./kWh. It should be noted that current policy addresses only carbon emissions at the point of generation, aiming for virtually 'zero-carbon' electricity by 2050 [29]. Both 100%-1 and 100%-2 are in line with this goal, emitting just 0.174 Mt CO_2 each in 2050 in direct carbon emissions. However, when the whole life cycle is considered, the 2070 mix of 100%-1 has a carbon footprint twice that of 100%-2 (14.2 vs 6.8 Mt CO_2 eq.). This is due to 100%-1's higher reliance on solar PV which, even in 2070, has a GWP of around 49 g CO_2 eq./kWh compared to 4.7 g for wind and 6.2 g for nuclear power (see Appendix 7). The 80% sub-scenario in fact has a lower total GWP in 2070 than the 100%-1 sub-scenario (12.0 vs 14.2 Mt CO_2 eq.) due to its greater use of nuclear power.

9.4.2.3 Ozone layer depletion potential (ODP)

ODP is lower than the present in all scenarios, particularly 80%-1 and 100%-2. The relatively high ODP of 100%-1 (2.46 t CFC-11 eq. per year) is, as discussed in Section 8.4.2.3, due to demand for tetrafluoroethylene in the solar PV life cycle. However, even this level of ozone layer depletion is 11% lower than today's. Moreover, by 2070 the mix of solar PV technologies will likely include a greater contribution from laminates (such as CIGS), which have lower ODP values (see Appendix 3), meaning the figure of 2.46 t is likely an overestimate. The best scenario from the ODP perspective is 80%, with an emission rate of 2.5 µg CFC-11 eq./kWh.

9.4.2.4 Acidification potential (AP)

Decreased acidification potential is seen in all scenarios compared to the present, with sub-scenario 100%-2 being the preferred outcome, reducing acid gas emissions by 192,000 t SO_2-equivalent per year relative to today: a reduction of 82%. The 65%-1 and 65%-2 sub-scenarios have the highest AP values in 2070 due to the extensive use of coal CCS; however, at 0.44 and

0.28 g SO_2 eq./kWh, respectively, they still represent reductions over the 2009 value of 29% (for 65%-1) and 55% (for 65%-2).

9.4.2.5 Eutrophication potential (EP)

All scenarios show at least a 57% improvement over today's electricity mix in terms of eutrophication. In this case, the renewables-intensive 100%-1 sub-scenario is the weakest, but all five are quite similar, emitting between 10 and 15 kt PO_4^{3-}-equivalent per year (0.021-0.032 g PO_4^{3-}eq./kWh) compared to the present day figure of 37 kt (or 0.099 g PO_4^{3-}eq./kWh).

9.4.2.6 Photochemical oxidant creation potential (POCP)

In terms of POCP, sub-scenarios 100%-2 and 80% are the best options, with POCPs of 5.4 and 8.8 kt C_2H_4 eq./yr, or 0.011 and 0.018 g C_2H_4 eq./kWh, respectively. The 2070 electricity in 65%-1 has the highest POCP (21.7 kt C_2H_4 eq./yr, or 0.048 g C_2H_4 eq./kWh), which is in fact slightly higher (~2%) than 2009's total annual POCP. This is due to very high emissions of NMVOCs, methane, sulphur dioxide and nitrogen oxides in the coal CCS life cycle.

9.4.2.7 Water eco-toxicity

<u>Freshwater eco-toxicity potential (FAETP)</u>

Sub-scenario 100%-2 illustrates that extreme carbon reduction can had adverse environmental effects by being the worst scenario in terms of freshwater eco-toxicity potential. This is because it relies heavily on nuclear power (50% of electricity by 2070), which has high FAETP due to emission of heavy metals during uranium mining and milling (see Section 4.4.2.7). By 2070, FAETP in 100%-2 is in fact 77% higher than that attributable to the present-day electricity mix (7.40 vs 4.17 Mt DCB eq./yr). The impact per unit output increases from 11.1 to 15.3 g DCB eq./kWh. However, FAETP is also higher than today's in every other scenario, including those with no nuclear power. This is because wind, solar and coal CCS all have relatively high FAETPs relative to the natural gas power that dominates today's mix. This is a clear example of a sustainability trade-off: reducing carbon emissions is very likely to increase freshwater eco-toxicity, regardless of how it is achieved. Gas power with CCS may alleviate this problem, but has not been considered in the present study.

Marine eco-toxicity potential (MAETP)

As shown in Figure 37 (Section 9.1.2.2), the MAETP of the current electricity mix is completely dominated by coal power which causes 93% of the total, mainly due to aerial emissions during the operational stage. Similar emissions also apply to coal CCS, therefore any scenario involving coal CCS is similarly toxic to marine environments. This is illustrated in 65%-1 which, in 2070, derives 55% of its electricity from coal CCS and emits 110 Gt DCB-equivalent per year (or 242 kg DCB eq./kWh): a total annual increase of 55% over the present-day mix. In contrast, the best scenario in terms of MAETP (100%-1) emits only 17.1 Gt DCB eq./yr (or 35 kg DCB eq./kWh).

9.4.2.8 Land use and quality

Terrestrial eco-toxicity potential (TETP)

Like freshwater eco-toxicity potential, TETP is higher in all 2070 scenarios than in the present, although this is mainly due to an increase in electricity demand rather than an increase per unit output. The worst scenario from this perspective is 65%-1 with total emissions 86% higher than in 2009 (507 vs 273 kt DCB eq./yr) and emissions per kilowatt-hour 50% higher than the present (1.11 vs 0.73 g DCB eq./kWh). This is mostly due to coal CCS. However, even in scenarios with very little coal CCS, FAETP is higher than in 2009 due to increased electricity use: in 100%-1, for example, annual emissions of toxic compounds to land are 13% higher than in the present day due to heavy metal emissions in the life cycles of nuclear, wind and solar power despite emissions per kilowatt-hour being 13% lower. Thus, future increases in TETP are highly likely.

Land occupation

As shown in Appendix 7, land occupation in the coal and coal CCS life cycles is far higher than that of any other technology due to the large volume of coal required and, consequently, the large area of land devoted to mining. As a result, scenarios with a significant coal or coal CCS component (65%-1 and 65%-2) have the greatest life cycle land occupation. In the case of 65%-1, 75% more land occupation is required than in the present day (5734 vs 3276 km^2yr/yr, or 0.0126 vs 0.0087 m^2yr/kWh). According to this indicator, 100%-2 is the best option with total land occupation of 451 km^2yr/yr, or 0.00093 m^2yr/kWh.

Greenfield land use

As stated in Section 9.2.2, greenfield land use has not been quantified in this scenario analysis because future power plant sites are unknown beyond the next decade or so.

9.4.3 Social sustainability

This sub-section considers the social sustainability results of the scenario analysis for the year 2070, with the 2009 electricity mix included for comparison. The results are presented in Figure 51 (per year) and Figure 52 (per unit of electricity generated) and are discussed below.

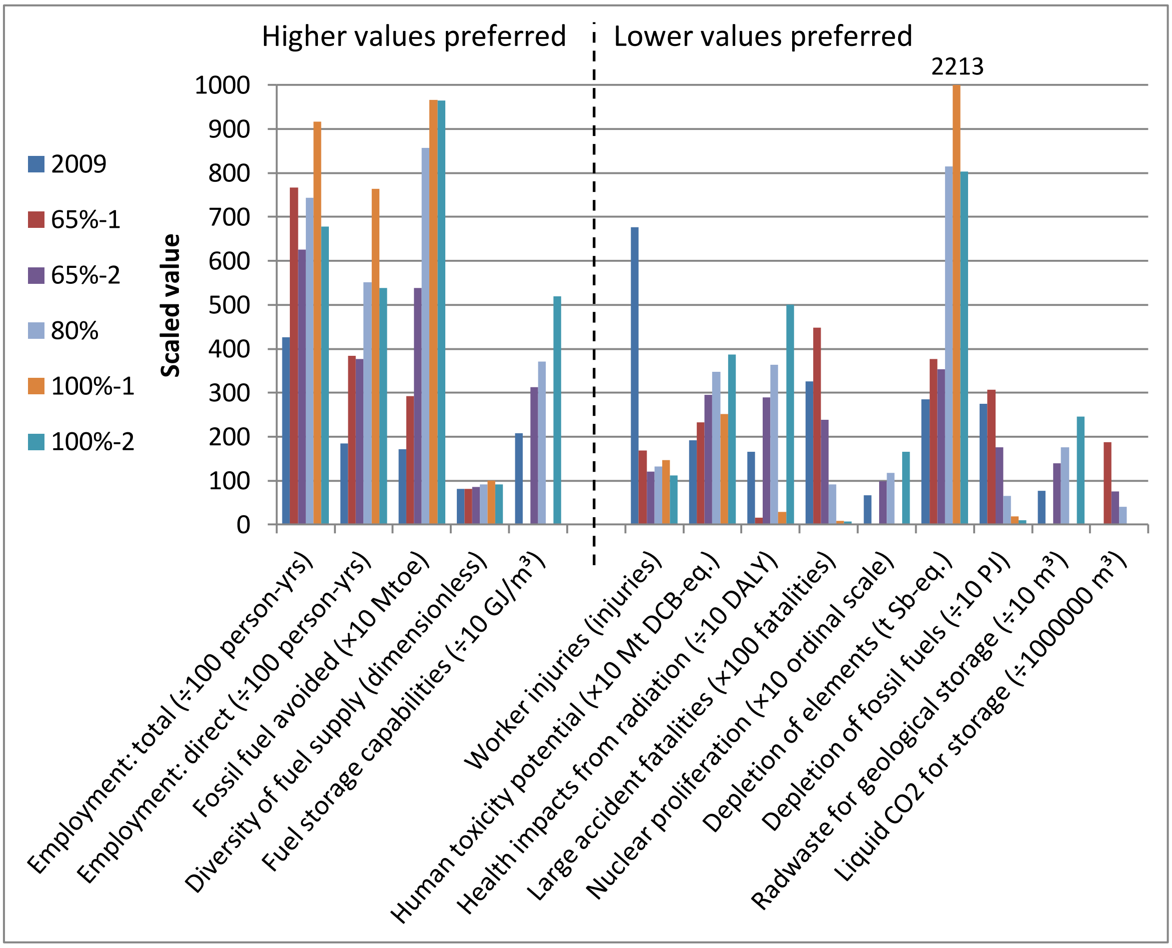

Figure 51: Social comparison of potential future electricity mixes for the UK, expressed per year. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. For full results, see Appendix 8.

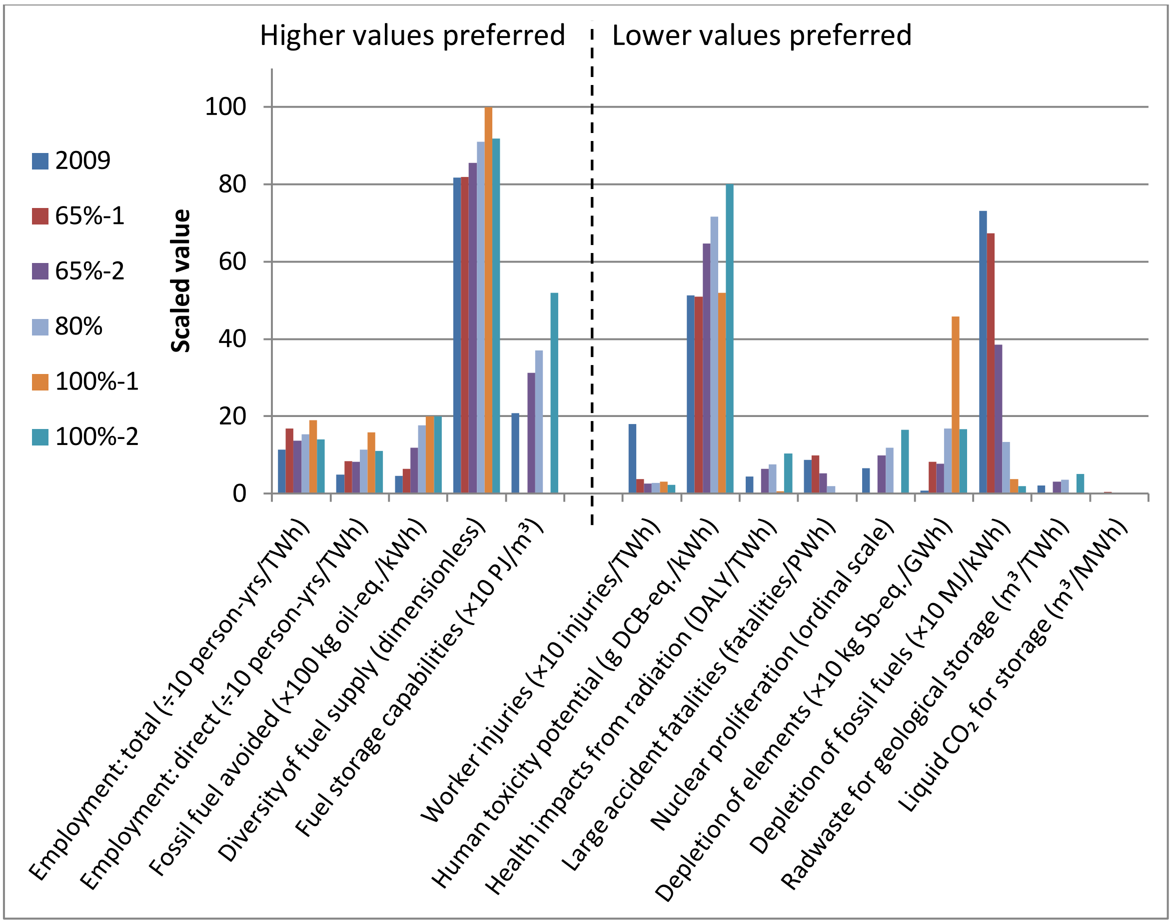

Figure 52: Social comparison of potential future electricity mixes for the UK, expressed per unit electricity generated. For indicators left of the dotted line, higher values are better; for indicators to the right, lower values are preferred. Some indicators have been scaled up or down to be viewed more easily by multiplying or dividing their original values by the factor shown in brackets. For full results, see Appendix 8**.**

9.4.3.1 Provision of employment

Total employment

The total employment estimates in Figure 51 and Figure 52, which include raw material extraction, manufacturing, construction, operation and maintenance, and decommissioning, show that all 2070 scenarios provide more employment than the present, but to varying degrees. Sub-scenarios 100%-1 and 65%-1 provide the most employment at 91,700 and 76,700 jobs, respectively (or 189 and 168 person-yrs/TWh), compared to the 2009 figure of 42,700 (or 114 person-yrs/TWh). This trend of growing employment reflects in large part the decline of natural gas power, which provides the fewest jobs of the options considered (see Section 9.1.1). However, nuclear power is estimated to provide only 30% more employment than gas power (see Section 4.4.3.1), meaning scenarios with high nuclear penetrations provide fewer jobs than those that rely on alternatives such as renewables or coal CCS.

Direct employment

When indirect employment is excluded from the total, the trend is similar. However, the results demonstrate that most of the employment provided by 65%-1 and 65%-2 is indirect: when raw material extraction and manufacturing are excluded, 65%-1's employment drops by 50% to 38,300 jobs (or 84.2 person-yrs/TWh) and it is overtaken by scenarios 80% and 100%-2. This is caused by the reliance of the 65%-1 electricity mix on coal CCS (55% of electricity by 2070), reflecting the fact that around 70% of jobs in the coal CCS life cycle are thought to be in the coal mining stage. In contrast, the majority (80-85%) of jobs in the wind and solar life cycles are in O&M or installation, meaning the exclusion of indirect employment has little effect. This also means that, in the renewable-intensive scenarios (80%, 100%-1 and 100%-2), more of the total employment is likely to be in the UK. The most direct employment is provided by 100%-1: 76,400 jobs (or 158 person-yrs/TWh).

9.4.3.2 Human health impacts

Worker injuries

By 2070, projected improvements in worker injury rates (see Section 9.2.3) mean that injuries are much less frequent than in 2009 across all scenarios. The number of injuries varies from 111 per year (in 100%-2) to 169 per year (in 65%-1), corresponding to 0.23 and 0.37 injuries/TWh, respectively. The range reflects the fact that, even in 2070, coal mining is still a relatively dangerous occupation and therefore that coal CCS is more dangerous than other energy chains.

Human toxicity potential (HTP), excluding radiation

Of the options assessed, nuclear power has the highest HTP in 2070. As a result, the scenario with the most nuclear power (100%-2) has the highest toxicological impact on human health: approximately twice that of today's electricity mix (38.7 vs 19.2 Mt DCB eq./yr). However, the lowest HTP of the technologies assessed belongs to natural gas power (see Appendix 7), which provides virtually no electricity by 2070 due to its excessive carbon emissions. This, combined with the higher electricity demand in 2070, means that all scenarios are worse than the present in terms of total HTP (although per kilowatt-hour 65%-1 and 100%-1 are within 1.3% of the present). This, like freshwater and terrestrial eco-toxicity, is an example of a probable trade off in exchange for lower carbon emissions.

Total human health impacts from radiation

As discussed in Section 4.4.3.2, nuclear power has a much greater radiation-induced health impact than other technologies. As a result, 65%-1 and 100%-1, which lack nuclear power, are the best options in this respect, causing 163 and 293 DALYs annually, respectively, compared to 1657 DALYs in 2009. The scenario with the most nuclear power, 100%-2, results in approximately 5000 DALYs per year by 2070 (although this figure in fact peaks in 2050 at 5180 DALYs when electricity demand is higher). This equates to 10.4 DALYs/TWh compared to 4.4 in the present-day. This impact is mainly due to uranium mill tailings and occurs over a period of thousands of years (see Section 4.4.3.2).

9.4.3.3 Large accident risk

Fatalities due to large accidents

As shown in Figure 51, scenario 65%-1 causes the most fatalities due to large accidents at 4.48 per year, or 9.84 fatalities/PWh. The estimate of 4.48 fatalities/year is 38% higher than today's. This is because 65%-1 relies heavily on coal CCS which, in 2070, is estimated to cause over 50 times more fatalities per unit of electricity generated than offshore wind, solar PV or nuclear power. This is a direct result of its high coal mining requirement. The best option from this perspective is 100%-2 due to its use of renewables: it causes 0.063 fatalities/year, or 0.13 fatalities/PWh.

9.4.3.4 Local community impacts and human rights & corruption

As mentioned in Section 9.2.3, these impacts have not been considered because they are company-specific and therefore not applicable to generic technology assessments. For further discussion, see Section 3.2.3.

9.4.3.5 Energy security

Avoidance of fossil fuel imports

The carbon constraints of the scenarios mean that, even accounting for coal CCS, fossil fuel use cannot be as high in 2070 as in 2009. Clearly, however, scenarios 100%-1 and 100%-2 avoid the most fossil fuel use due to 99.8% of electricity coming either from renewables or nuclear power in 2070. Relative to the 2009 fossil fuel fleet, this saves 97 million tonnes of oil equivalent per year. Clearly this would represent a national increase in resilience to fossil fuel price volatility. Even the less extreme 80% scenario saves 86 Mtoe/year relative to the 2009 fossil fleet.

Diversity of fuel supply mix

This indicator reflects the resilience of national electricity production to fuel supply disruptions, whether they are economic, technical or political. However, results here are highly tentative as future fuel supply mixes cannot be known. Assuming, however, that supply mixes stay the same as in the present, resilience increases with renewable penetration, meaning 100%-1 has the highest result at 99.9% compared to the average 2009 value of 81.8%. However, as UK steam coal currently has the least diverse fuel supply (see Section 6.4.3.5), any electricity mix with little coal or coal CCS is preferable: for example, the 80% scenario scores 91.0% despite only 53% of electricity coming from renewable sources in 2070.

Fuel storage capabilities

The fuel storage abilities of nuclear power far exceed any other electricity source (see Section 4.4.3.5). Therefore it is far easier to stockpile energy reserves in scenarios with large amounts of nuclear power. Consequently, 100%-2 has the highest effective fuel storage potential at 5.19 PJ/m^3, 149% higher than today's electricity mix (2.08 PJ/m^3). In contrast, it is not possible to stockpile fuel in scenario 100%-1 as it relies almost entirely on renewables. However, as renewables have no fuel, the main energy security obstacle to renewable-intensive scenarios is their variable output and the resulting difficulty of matching supply to demand.

9.4.3.6 Nuclear proliferation

Use of non-enriched uranium, reprocessing and requirement for enriched uranium

Clearly the result of this indicator increases proportionately with nuclear power's contribution to the energy mix, meaning scenario 100%-2 carries the greatest proliferation risk due to 50.1% of its electricity coming from nuclear power stations by 2070. Its proliferation risk is rated at 16.5% relative to today's rating of 6.6%. However, as discussed in Section 4.4.3.6, if reprocessing of spent fuel occurs the rating would double due to the extracted products becoming potential targets of theft or terrorism. As noted in Section 3.2.3.7, the ordinal scale used here is simplistic and is not appropriate for the evaluation of any Generation IV reactors that may or may not be online by 2070.

9.4.3.7 Intergenerational equity

Use of abiotic resources (elements)

Depletion of elements is positively correlated with renewable electricity output because wind and solar power have a much higher life cycle impact than other power sources. This is demonstrated in 100%-1, the renewable-intensive scenario, in which depletion amounts to 2,213 t Sb-equivalent per year (or 4.58 kg Sb eq./GWh), 6.8 times the amount in 2009. This is due to the higher metal requirements of the renewables relative to their electrical output. However, clearly end-of-life recycling can reduce this depletion considerably (see Appendix 3). Less renewable-intensive scenarios, such as 80%, show a more modest increase over the present, but depletion increases in all scenarios.

Use of abiotic resources (fossil)

The depletion of fossil resources is obviously greatest in the life cycles of coal, coal CCS and gas power. Therefore fossil resource depletion is lowest in scenarios 100%-1 and 100%-2 which deplete around 185 and 95 PJ of fossil fuel per year, respectively (or 0.383 and 0.196 MJ/kWh). This compares to 2750 PJ (or 7.32 MJ/kWh) in the 2009 electricity mix, equating to a saving of 97% for 100%-2 and 93% for 100%-1. The less extreme 80% scenario also results in significant improvements over the present with a value of 649 PJ/yr (or 1.34 MJ/kWh). The result is that far more fossil fuel would be available for use by future generations.

Volume of radioactive waste and liquid CO_2 to be stored

The most nuclear-intensive scenario, 100%-2, has an operating nuclear capacity of around 32.5 GW in 2070 producing a total of 2460 m^3 of radioactive waste per year requiring geological storage. This is around 2.2 times as much as the equivalent amount for 2009 (although, as noted in Section 9.1.2.3, this 2009 figure is based on PWRs and therefore does not accurately reflect the amount of waste produced by the current UK nuclear fleet). It should be noted that this figure is based on a ‘once-through’ cycle in line with current policy, in which no reprocessing of fuel occurs; if this changes in the future, the waste produced would be much lower in volume but with higher heat output, necessitating greater packaging space per unit volume [367].

Scenario 65%-1 has the greatest contribution from coal CCS and therefore produces the most CO_2 in need of storage. In 2070, this amounts to 187.5 million m^3 per year of supercritical, pressurised CO_2.

9.4.4 Summary of sustainability assessment of future UK electricity scenarios

In an attempt to summarise the above results and compare the scenarios on their overall sustainability performance, Table 47 shows the ranking of each 2070 electricity mix against each indicator. The 2009 mix is also included for comparison. The total ranking of each scenario is also shown, estimated by summing the individual rankings for each indicator, assuming equal weighting for all indicators. This is a simplistic analysis that does not properly account for stakeholder preferences. Moreover, there is not consideration of the distribution of individual indicator scores between different options. The overall result is also biased in favour of techno-economic and social impacts due to the fact that the environmental group has the fewest indicators. These problems could be addressed using multi-criteria decision analysis (MCDA), but this is beyond the remit of this research and should be a focus of potential future work.

Within the above limitations, scenarios 100%-1 and 100%-2 appear to be the most sustainable options with summed ranks of 110 and 108, respectively. The third best option is the 80% scenario with 124, followed by 65%-2 with 132. The 65%-1 scenario is the only one to appear less sustainable than the present day mix, with 144 compared to 135 for 2009.

It is important to note that, as discussed in Sections 9.3.3.1 and 9.3.3.2, both scenarios 100%-1 and 100%-2 (particularly the former), would be untenable without an extremely large capacity of energy storage and demand-side management the likes of which are not currently available. This would inevitably have consequences, such as increased costs and environmental impacts due to infrastructure requirements, but the extent of these impacts are unknown and are beyond the scope of this study. Particularly in the case of 100%-1, the limited number of technologies considered in this work constrains the accuracy of the assessment: other technologies, such as biomass, would need to be considered in order to confidently predict the outcomes of such an extremely renewable-intensive scenario.

Nevertheless, the analysis suggests that a stakeholder with a techno-economic bias would likely favour the present-day mix or 65%-2. Conversely, an environmentally biased stakeholder would likely select scenarios 80%, 100%-1 or 100%-2, bearing in mind the caveats above, as they all have summed ranks below 30 (compared to over 40 for the other three electricity mixes). Finally, from the social perspective 100%-1 appears to be the best outcome with a summed rank of 32 compared to 46-56 for the other options. Again, the variability of 100%-1 and 100%-2 make these conclusions very tentative and suggest that further work in the field of demand-side management and energy storage are required to arrive at robust decisions. This work is suggested in Section 10.3.

Table 47: Ranking of each scenario in 2070 against each indicator

Category	Issue addressed	Indicator	Unit	2070 electricity mix: 2009 mix	65%-1	65%-2	80%	100%-1	100%-2
Techno-economic	**Operability**	1. Capacity factor (power output as a percentage of the maximum possible output)	Percentage (%)	1	5	2	4	6	3
		2. Availability factor (percentage of time a plant is available to produce electricity)	Percentage (%)	6	5	4	2	1	3
		3. Technical dispatchability (ramp-up rate, ramp-down rate, minimum up time, minimum down time)	Summed rank	1	2	3	4	6	5
		4. Economic dispatchability (ratio of capital cost to total levelised generation cost)	Dimensionless	1	2	3	4	6	5
		5. Lifetime of global fuel reserves at current extraction rates	Years	1	3	2	5	6	4
	Technological Lock-in	6. Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/thermochemical H_2 production) and operational lifetime	Years^{-1}	1	2	3	4	6	5
	Immediacy	7. Time to plant start-up from start of construction	Years	6	4	5	2	1	3
	Levelised Cost of Generation	8. Capital costs	Pence/kWh	1	3	2	5	6	4
		9. Operation and maintenance costs	Pence/kWh	1	6	2	5	4	3
		10. Fuel costs	Pence/kWh	6	5	4	3	1	2
		11. Total levelised cost	Pence/kWh	1	4	2	5	6	3
	Cost Variability	12. Fuel price sensitivity (ratio of fuel cost to total levelised generation cost)	Dimensionless	6	5	4	3	1	2
	Financial Incentives	13. Financial incentives and assistance (e.g. ROCs, taxpayer burdens)	Pence/kWh	-	-	-	-	-	-
			Techno-economic summed rank	**32**	**46**	**36**	**46**	**50**	**42**

Environmental	**Material Recyclability**	14. Recyclability of input materials	Percentage (%)	6	4	5	2	1	3
	Water Eco-toxicity	15. Freshwater eco-toxicity potential	kg 1,4 DCB‡ eq./kWh	1	2	4	5	3	6
		16. Marine eco-toxicity potential	kg 1,4 DCB‡ eq./kWh	5	6	4	3	1	2
	Global Warming	17. Global warming potential (GHG emissions)	kg CO_2 eq./kWh	6	4	5	2	3	1
	Ozone Layer Depletion	18. Ozone depletion potential (CFC and halogenated HC emissions)	kg CFC-11 eq./kWh	6	4	3	2	5	1
	Acidification	19. Acidification potential (SO_2, NO_x, HCl and NH_3 emissions)	kg SO_2 eq./kWh	6	5	4	2	3	1
	Eutrophication	20. Eutrophication potential (N, NO_x, NH_4^+, PO_4^{3-} etc.)	kg PO_4^{3-} eq./kWh	6	3	4	2	5	1
	Photochemical Smog	21. Photochemical smog creation potential (VOCs and NO_x)	kg C_2H_4 eq./kWh	5	6	4	2	3	1
	Land Use & Quality	22. Land occupation (area occupied over time)	m^2yr/kWh	5	6	4	3	2	1
		23. Greenfield land use (proportion of new development on previously undeveloped land relative to total land occupied)	Percentage (%)	-	-	-	-	-	-
		24. Terrestrial eco-toxicity potential	kg 1,4 DCB‡ eq./kWh	1	6	5	4	2	3
			Environmental summed rank	**47**	**46**	**42**	**27**	**28**	**20**
Social	**Provision of Employment**	25. Direct employment	Person-years/GWh	6	4	5	2	1	3
		26. Total employment (direct + indirect)	Person-years/GWh	6	2	5	3	1	4
	Human Health Impacts	27. Worker injuries	No. of injuries/TWh	6	5	2	3	4	1
		28. Human toxicity potential (excluding radiation)	kg 1,4 DCB‡ eq./kWh	1	2	4	5	3	6
		29. Human health impacts from radiation (workers and population)	DALY¥/GWh	3	1	4	5	2	6
	Large Accident Risk	30. Fatalities due to large accidents	No. of fatalities/GWh	5	6	4	3	1	2
	Local Community Impacts	31. Proportion of staff hired from local community relative to total direct employment	Percentage (%)	-	-	-	-	-	-
		32. Spending on local suppliers relative to total annual spending	Percentage (%)	-	-	-	-	-	-
		33. Direct investment in local community as proportion of total annual profits	Percentage (%)	-	-	-	-	-	-
	Human Rights and Corruption	34. Involvement of countries in the life cycle with known corruption problems (based on Transparency International Corruption Perceptions Index)	Score (0-10)	-	-	-	-	-	-

Energy Security	35. Amount of imported fossil fuel potentially avoided	toe/kWh	6	5	4	3	1	2
	36. Diversity of fuel supply mix	Score (0-1)	6	5	4	3	1	2
	37. Fuel storage capabilities (energy density)	GJ/m^3	4	5	3	2	6	1
Nuclear Proliferation	38. Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	Score (0-3)	3	1	4	5	1	6
Intergenerational Equity	39. Use of abiotic resources (elements)	kg Sb eq./kWh	1	3	2	5	6	4
	40. Use of abiotic resources (fossil fuels)	MJ/kWh	5	6	4	3	2	1
	41. Volume of radioactive waste to be stored	m^3/kWh	3	1	4	5	1	6
	42. Volume of liquid CO_2 to be stored	m^3/kWh	1	6	5	4	2	2
		Social summed rank	**56**	**52**	**54**	**51**	**32**	**46**
		TOTAL SUMMED RANK	**135**	**144**	**132**	**124**	**110**	**108**

‡DCB – dichlorobenzene; ¥DALY – disability-adjusted life years

9.5 Summary

This chapter has explored the application of the sustainability assessment framework developed in this research to different future electricity mixes in the UK. The assumptions for the different scenarios considered can be summarised as follows:

- 65%-1 and 65%-2 depict futures in which limited action is taken to mitigate climate change. The UK does not meet its 2050 target of an 80% reduction in emissions (although electricity does decarbonise by 65% by 2050 relative to 1990). In 65%-1, new nuclear build does not occur; coal CCS is the dominant technology, providing 55% of electricity by 2070. In 65%-2, nuclear build does occur, leading to a mix quite evenly split between nuclear, coal CCS, gas and renewables.
- The 80% scenario describes a future in which the electricity sector achieves emissions reductions of 80% by 2050. Only one sub-scenario is considered in this case (also referred to as 80%), in which the 2070 mix is dominated by renewables and nuclear power with coal CCS providing a smaller share.
- 100%-1 and 100%-2 consider futures in which the UK meets its carbon targets by greatly decarbonising the electricity sector and partly switching other services (such as heating and transport) over to electricity. As a result, electricity is virtually zero carbon at the point of generation by 2050, in line with the Carbon Plan. 100%-1 achieves this using only renewables and a very small amount of coal CCS, while 100%-2 relies more heavily on nuclear power (50% of electricity by 2070).

The outcomes of the scenario assessment are as follows:

- Availability (and thus reliability) increases with renewable penetration, meaning scenario 100%-1 is preferable. However, this comes at the expense of dispatchability, meaning it becomes harder to match supply to demand. This would not be possible in 100%-1 without huge amounts of energy storage and, probably, biomass plants used specifically for load-following. The impacts of this have not been considered in this study and are suggested as a source of future work.
- Overall costs are higher than the present in all scenarios. However, even taking into account cost reduction via learning rates, 100%-1 is the most expensive (55% more costly than the 2009 mix per kilowatt-hour). 65%-2 is the cheapest. As above, however, the increased costs of energy storage, balancing mechanisms and output restrictions are currently unknown.

- Lower carbon electricity mixes tend to be more capital intensive, meaning willingness to invest at reasonable interest rates becomes more important if carbon reductions can be achieved. This illustrates the importance of initiatives like the UK Green Investment Bank.
- 80%, 100%-1 and 100%-2 are all at least 87% less sensitive to fuel price changes than the present electricity mix. This should significantly reduce the volatility of electricity prices.
- The level of incentives required to achieve any of the scenarios is difficult to predict. However, costs of generating electricity from offshore wind and solar PV in 2070 should be around 40% and 75% lower than in the present, meaning incentives can be greatly reduced or eliminated.
- From the environmental point of view, 100%-2 is the best option according to seven of the ten indicators.
- Every scenario improves on the environmental impacts of 2009, excluding freshwater eco-toxicity (100%-2 is 77% worse than today), marine eco-toxicity (65%-1 is 55% worse than today), land toxicity (65%-1 is 80% worse than today) and land occupation (65%-1 is 75% worse than today).
- Freshwater and land toxicity are in fact worse in 2070 than in 2009 for every scenario. This is due to the high metal requirements of renewables and their associated emissions, as well as emissions from uranium mill tailings and coal mining and combustion.
- Total employment is highest in 100%-1 and 65%-1 due mainly to the manufacture/O&M of renewables and coal mining, respectively. However, direct employment (i.e. that more likely to be in the UK) is much higher in 100%-1. Total employment is 47-115% higher than the present in all scenarios.
- Injury rates decrease in future, but 65%-1 still causes 52% more worker injuries than 100%-2 due to coal mining. In terms of large accident fatalities, 65%-1 is in fact 38% worse than the 2009 energy mix.
- Human toxicity and the depletion of elements are higher than the present in all scenarios.
- Energy security is clearly better in scenarios with less fossil fuel (80%, 100%-1 and 100%-2). However, highly renewable mixes (such as 100%-1) suffer from the variable output problem discussed above, meaning overall security may be diminished.
- In terms of intergenerational equity, the worst scenarios are 100%-2 (due to nuclear waste storage requirements) and 65%-1 (due to CO_2 storage requirements). In 2070, 100%-2 produces around 2500 m^3 of packaged waste per year in need of geological disposal. 65%-1 produces 187.5 million m^3 per year of supercritical CO_2.

- By ranking the scenarios against each indicator and assuming equal weighting for all impacts, 100%-1 and 100%-2 appear to be the most sustainable choices. However, the unknown impacts of the energy storage and demand-side management required by electricity mixes with low dispatchability reduce confidence in this conclusion. Moreover, the outcome is different for different stakeholders: techno-economic bias favours the present-day mix or the 65%-2 mix; environmental bias favours 80%, 100%-1 or 100%-2; and social bias favours 100%-1.

It is hoped that this analysis provides a useful input into future energy policy. Specific policy recommendations are made in the next and final chapter, which summarises the findings of the work as a whole.

10 Conclusions, recommendations & further work

This research has developed a life cycle sustainability assessment framework for application to various electricity technologies and scenarios, taking into account techno-economic, environmental and social aspects (Chapter 3). The framework has been applied, in the UK context, to individual technologies as well as different future scenarios. The former involved the sustainability assessment of five electricity options of interest to the UK: nuclear power (PWR), natural gas (CCGT), coal (subcritical pulverised), wind (offshore) and solar (residential PV) (Chapters 4-8). The assessment of future scenarios involved consideration of five potential UK electricity mixes, spanning 2020 to 2070, and comparison to the present day (Chapter 9). The scenarios depict three different approaches to climate change: one future in which little action is taken to reduce carbon emissions ('65%'), one in which electricity decarbonises by 80% by 2050 in line with the UK's broad carbon reduction target ('80%'), and one in which electricity is completely decarbonised (at the point of generation) by 2050, in line with current UK policy ('100%').

Therefore, the aims and objectives of this research as stated in Chapter 1 have been met as follows:

- sustainability assessment frameworks and indicators for electricity and related systems developed by other authors have been reviewed and critically examined (Chapter 2);
- a life cycle sustainability assessment framework and indicators applicable to different electricity options and mixes have been developed (Chapter 3); and
- the methodological framework and the sustainability indicators have been tested by carrying out sustainability assessments of different electricity options and scenarios for the UK (Chapters 4-9).

Based on the above, policy recommendations (also one of the objectives of the work) have been made using the results of the sustainability assessments; these are given in Section 10.2. Prior to that, the overall conclusions of this work are summarised in Section 10.1. Finally, suggested areas for future work are given in Section 10.3.

10.1 Conclusions

This section summarises the conclusions that can be drawn from this work regarding the comparative sustainability assessment of electricity technologies and potential future scenarios for the UK.

10.1.1 Sustainability of technologies in the present

10.1.1.1 Techno-economic aspects

- Gas (CCGT) is the cheapest option (excluding incentives) at around £66/MWh but has the highest cost variability due to its high fuel component (74% of total costs). This is becoming particularly relevant as UK gas production declines and reliance on liquefied natural gas (LNG) from the international market increases. Traditional coal power costs around £74/MWh and is less sensitive to fuel price changes: the fuel component is about 30% of the total. Nuclear power is more expensive for the immediate future (£95/MWh) and has a much bigger capital component (around 80%), meaning that it becomes less attractive at higher discount rates. It is, however, virtually insensitive to fuel price changes: fuel makes up around 6% of total costs. Offshore wind has higher costs (£146/MWh), in part due to the high operation and maintenance costs incurred as owners attempt to improve availability factors, which are currently the lowest of the technologies assessed (81% c.f. 87-96% for the other options). On the other hand, offshore wind is significantly cheaper than domestic PV, which is estimated at £498/MWh.
- The incentives currently available to offshore wind total 8.2 p/kWh. This compares to the 40.6 p/kWh received by recent PV systems. Therefore, the cost of making offshore wind competitive is currently 32.4 p/kWh lower than that of PV. Residential PV systems registered after April 2012 receive reduced incentives of 21 p/kWh following a government review, but even at this new level offshore wind is more cost effective. It should be borne in mind that all incentives are indirectly paid for by consumers.
- Natural gas and coal power are both highly dispatchable due to their low capital cost components and technical load-following ability (rated at 7.7 and 4.7, respectively, compared to 11.7 for nuclear power, lower scores being preferable). Gas power plants in particular are also quick to build (around 37 months) and resistant to technological lock-in due to their relatively short lifetime (20-30 years) and high temperature heat

production. Nuclear power has quite low dispatchability, but this is mainly due to its large capital cost component discussed above, meaning partial load-following is possible if peak electricity prices are sufficiently high. However, the long lifetimes (60 years) and relatively low temperatures of nuclear plants mean that technological lock-in is a potential concern (although not as much as for wind and solar PV, as they produce no heat at all).

- As wind power is non-dispatchable, costs depend heavily on capacity factors, which are currently about 30% but should be higher for newer, larger turbines. Solar PV is also non-dispatchable, but the fact that variations in output more closely match variations in electricity demand should mitigate this problem somewhat. The capacity factor of solar PV in the UK is low (around 9%) due to relatively low insolation. The capacity factor for nuclear power is 85%, while that of coal and gas is 62% in both cases.
- Fuel reserve lifetimes range from approximately 60 years for natural gas to an effectively infinite supply for solar and wind power. Coal reserves are expected to last around 120 years at current usage rates. Nuclear fuel reserves are about 80 years using the 'once-through' fuel cycle proposed in the UK, but could increase to 675 years with unconventional resources or 34,000 years with fast breeder reactors.

10.1.1.2 Environmental aspects

- Nuclear and offshore wind are the best two options according to eight of the 11 environmental indicators considered. Wind is, however, the worst option in terms of freshwater eco-toxicity due to its high metal requirements, while nuclear power is the second worst due to long-term emissions of heavy metals from uranium mill tailings.
- Coal is the least sustainable option for seven of 11 impacts, including global warming potential.
- Nuclear and offshore wind have the lowest global warming potentials at 6.2 and 11.2 g CO_2 eq./kWh, respectively. These compare to 88 g for solar PV, 379 g for natural gas and 1072 g for coal.
- Compared to other technologies in this assessment, natural gas is environmentally the most sustainable in terms of freshwater, marine and terrestrial eco-toxicity potentials. However, as the contribution of LNG increases, so does the global warming potential of electricity from gas (up to 496 g CO_2 eq./kWh).
- PV performs relatively poorly with respect to environmental impacts, mainly due to the relatively low insolation in the UK which balances low electrical output against the high

energy and resource requirements of manufacture. PV has the highest ozone layer depletion potential as well as the second worst result in five of the remaining 10 indicators. However, many of these results can be improved significantly (on average, by around 25%) by recycling, as most impacts are accrued during resource extraction and processing.

10.1.1.3 Social aspects

- Solar PV provides the highest employment of the five options at approximately 650 person-years/TWh, but consequently the highest worker injuries (4.8/TWh). It also has the second highest human toxicity potential and highest depletion of abiotic elements, exceeding the next worst option (offshore wind) by a factor of 15.
- Offshore wind provides the second most employment (368 person-years/TWh), followed by coal, but most of the latter is in coal mining and, consequently, worker injury rates are high (4.5/TWh). Moreover, large accident fatalities in the coal life cycle are the highest of all options considered at 20.7 per TWh.
- Coal power has the worst result for diversity of fuel supply (0.71 compared to 0.84 for nuclear and 0.87 for gas), mainly due to over-reliance on imports from Russia.
- Gas power has the lowest human toxicity potential, worker injuries and depletion of elements.
- Nuclear power has the second lowest life cycle employment (80 person-yrs/TWh vs 62 for gas), the highest health impact from radiation and arguably the greatest intergenerational impact, producing ~6000 m^3 of waste requiring geological storage per reactor lifetime (although this should be balanced against its low global warming potential). It also creates a proliferation risk which, with current UK policy and reactor proposals, is rated at 0.33 out of a maximum of one.
- Nuclear power also has the potential to cause the highest number of fatalities in a single incident, although in terms of the rate of large accident fatalities it is the best option, causing nearly 17,000 times fewer fatalities than the coal life cycle (0.00122 vs 20.7 fatalities/PWh).
- Nuclear power scores highly for the energy security indicators, particularly due to the ability to stockpile 290 million times more energy per unit volume than natural gas. Additionally, nuclear, offshore wind and PV avoid the use of approximately 0.2 kg oil eq./kWh relative to the current UK fleet of coal and gas plants. This reduces the country's reliance on imported fuel.

- When fossil fuel use throughout the life cycle is considered, the five technologies deplete 0.08-15.1 MJ/kWh, with nuclear being the best option in this respect and coal the worst.

10.1.2 Future technologies and scenarios

10.1.2.1 Techno-economic aspects

- Overall costs are higher than the present in all scenarios analysed. Even though cost reductions are incorporated for developing technologies, the most expensive is the most renewable-intensive scenario (100%-1) which, by 2070, costs 55% more per kilowatt-hour than the 2009 mix. The scenario with a balanced mix mainly comprising nuclear, coal CCS and renewables (65%-2) is the cheapest (but does not meet carbon targets).
- However, in all the low-carbon scenarios (80%, 100%-1 and 100%-2), the variable output and non-dispatchability of renewables means that additional costs would be incurred for energy storage, balancing mechanisms and output restrictions. The impact this would have on economics and on other sustainability indicators is unclear and is suggested as a subject of future work.
- Lower-carbon electricity mixes tend to be more capital intensive, meaning finding sufficient investment will be more challenging in future; this illustrates the importance of initiatives like the UK Green Investment Bank.
- The low-carbon scenarios (80%, 100%-1 and 100%-2) are all at least 87% less sensitive to fuel price changes than the present electricity mix. This should significantly reduce the volatility of electricity prices.
- The overall availability factor of the electricity mix increases in all scenarios due to higher renewables penetration, meaning fewer unscheduled outages should occur. However, capacity factors decrease in renewable-intensive scenarios (declining from 66% in the present to 27% in 100%-1 by 2070) as output becomes more variable.
- The effective fuel reserve lifetime of the electricity mix is longer in all scenarios than in the present due to increasing penetration of renewables. At current usage rates, uranium reserves will only last until around 2090 unless new sources, potentially including phosphates, are exploited.
- All future scenarios are less resistant to technological lock-in than the present, mainly due to the long lifespans of nuclear plants and the lack of heat available from renewable sources. In the most renewable-intensive scenario (100%-1), the lock-in resistance rating

declines from 10.5 yrs^{-1} in the present to 0.02 yrs^{-1} in 2070, meaning the electricity sector is less able to respond to changes in energy use patterns.

10.1.2.2 Environmental aspects

- Increasing the penetration of nuclear and renewables, as in scenario 100%-2, generally leads to better environmental performance; 100%-2 is the best option for seven out of ten indicators.
- The annual global warming potential of the electricity mix decreases in all scenarios despite an increase in electricity demand, with 100%-2 being the best option (reduction of 96%) and 65%-2 the worst (reduction of 70%). In the low-carbon scenarios (80%, 100%-1 and 100%-2) coal CCS cannot provide more than about 10% of electricity beyond 2050 due to its high carbon emissions relative to nuclear and the renewables.
- Total freshwater and terrestrial toxicity worsen in all future scenarios, although this is partly due to future increases in electricity demand. In the worst case, freshwater eco-toxicity increases by 38% per kilowatt-hour produced (in scenario 100%-2) and terrestrial eco-toxicity by 53% (scenario 65%-1). In the former case, this is mainly due to the high metal requirements (and consequent emissions) of renewables, as well as emissions from uranium mill tailings in the nuclear life cycle. In the latter case, coal mining and combustion for coal CCS are the main causes.
- Ozone layer depletion, acidification, eutrophication, photochemical smog, marine eco-toxicity and land occupation decrease in all future scenarios with the exception of scenario 65%-1 under which marine toxicity and land occupation increase by 28% and 44%, respectively. This is due to coal CCS providing 55% of electricity by 2070.
- On average, electricity generating units are more recyclable by 2070 than in 2009, potentially reaching over 99% recyclability (as in scenario 100%-1). However, as current recyclability is already quite high (86%), improving end-of-life recycling rates is likely to be more important than potential recyclability.

10.1.2.3 Social aspects

- Increasing the installed capacity of renewables increases employment, particularly in operation and maintenance, meaning much of the employment creation is likely to be in the UK. In the most renewable-intensive scenario (100%-1), total employment increases by 115% to 91,700 jobs. Of these, 83% are 'direct' jobs (in installation and operation/maintenance) that are likely to be based in the UK.

- Energy security is clearly better in scenarios with less fossil fuelled generation (such as 80%-1, 100%-1 and 100%-2). However, highly renewable mixes (such as 100%-1) suffer from the variable output problem discussed above, meaning overall security of supply may be diminished. The amount of fossil fuel avoided relative to the 2009 fossil fuel fleet totals 97 million tonnes of oil-equivalent per year by 2070 in scenarios 100%-1 and 100%-2 due to renewables and nuclear power replacing fossil capacity. In terms of fuel storage capabilities, scenario 100%-2 is the best option (149% better than 2009) due to high penetration of nuclear power; this provides security against supply disruptions.
- Worker injury rates, depletion of fossil fuels and large accident fatalities decrease in all cases, apart from scenario 65%-1 in which large accident fatalities increase by 38% relative to the present due to increased coal mining (for coal CCS).
- Human toxicity potential and health impacts from radiation tend to increase with nuclear penetration. In the most nuclear-intensive scenario (100%-2), by 2070 human toxicity is 100% higher than in the present and radiation impacts are 200% higher with an annual impact of 5000 disability-adjusted life years lost (note that these losses are global, not isolated to the UK). In nuclear-free scenarios (65%-1 and 100%-1), radiation impacts decline by at least 82% relative to 2009.
- Finally, in terms of intergenerational equity, the worst scenarios are those that rely heavily on nuclear and renewables (due to nuclear waste storage requirements and depletion of elements, respectively), such as 100%-2, and those that rely on coal CCS (due to CO_2 storage requirements), such as 65%-1. In 2070, the former scenario produces around 2500 m^3 of packaged waste per year in need of geological disposal and the latter generates 187.5 million m^3 per year of supercritical CO_2. However, depletion of elements is highest in scenario 100%-1, due mainly to the solar PV life cycle, with overall results 680% higher than for the present mix. This increases material scarcity for future generations.

10.1.2.4 Summary of future scenarios

- By ranking each scenario according to its sustainability impacts in 2070, the lowest-carbon options (100%-2 and 100%-1) appear to be the most sustainable (with summed ranks of 108 and 110, respectively). The worst option is that which is most reliant on coal CCS – scenario 65%-1 – with a summed rank of 144. However, this is a simplistic analysis in which all sustainability impacts are assumed to be equally important. For a more realistic aggregation of impacts, the use of multi-criteria decision analysis (MCDA) is recommended as part of future work. As discussed above, there is also considerable uncertainty in the impacts of the lowest-carbon scenarios due to the unknown level and type of grid balancing measures needed (such as energy storage, back-up capacity and smart grid features).

- With the above caveats, the present-day mix and scenario 65%-2 are favoured from the techno-economic perspective, while the environmental perspective favours the lower-carbon scenarios (80%, 100%-1 and 100%-2) and the social point of view favours the most renewables-intensive scenario, 100%-1.

10.2 Policy recommendations

The trade-offs highlighted by the results of this research illustrate that it is important to consider thoroughly a range of sustainability aspects, on a life cycle basis, to arrive at informed and robust decisions. In the context of the UK, several policy recommendations can be made based on this research:

10.2.1 General recommendations

- Assessments of a range of technical, economic, environmental and social impacts should be at the centre of the decision-making process regarding the UK's electricity supply to ensure that all relevant impacts have been considered.
- A life cycle approach is essential to ensure that there is no burden shifting or 'leakage' of impacts.

10.2.2 Recommendations for the immediate future

- An approach based purely on economics will favour natural gas power, resulting in volatile electricity prices, increased reliance on imported fuel, relatively high ozone layer depletion, low employment and a failure to meet carbon emissions targets. Despite the many advantages of gas power, this suggests that regulation discouraging fossil-fuelled electricity generation is desirable. This also includes shale gas, the role of which is currently being discussed in the UK. This recommendation is congruent with the government's decision to introduce a carbon floor price by 2013 to strengthen the current carbon tax (which has little effect on the relative costs of technologies).

- Subsidies (or incentives provided via regulation) are also necessary to encourage uptake of non-fossil technologies. However, under current UK regulations, they are skewed heavily towards solar photovoltaics. This remains the case even after introduction of the new, lower Feed-in Tariff rates from April 2012. Clearly this regulation is designed to promote 'green' electricity, but life cycle assessment and economic analysis suggest that incentives might be better directed towards wind and nuclear power (although other technologies not considered here may be equally preferable, such as wave and tidal power or biomass).
- As well as the generally higher costs of low-carbon technologies, there is also greatly increased investment risk due to the fact that they tend to be capital cost intensive. This risk must be reduced by government via market frameworks or direct subsidy. The recently introduced Green Investment Bank and the proposed 'contract-for-difference' system that will eventually replace the Renewable Obligation Order demonstrate that the government is addressing this.

10.2.3 Recommendations for sustainable electricity in the long term

- It is likely that attempts to reduce carbon emissions will worsen other impacts such as environmental toxicity, human toxicity and resource depletion (although the extent of the increase depends on the technologies chosen). These impacts tend to be due to the high resource requirements (particularly for metals) of wind power and solar PV and can therefore be reduced by end-of-life recycling. Improving UK demolition recycling rates should therefore be a priority. The government's current policy of increasing landfill tax should assist with this. However, it would be beneficial to introduce measures to increase demand for recycled goods by, for example, providing tax benefits for companies that use recycled materials.
- If carbon targets are to be met, the emissions of coal CCS are such that it cannot provide more than around 10% of electricity at any time in the next 60 years. The only way around this is to use coal CCS plants in the short to medium term and artificially shorten their lifetimes as emissions constraints tighten. Thus, if coal CCS plants become commercially available, their total installed capacity should be capped to avoid future revenue losses for owners.

- In scenarios with large penetrations of nuclear power, uranium supply might become a future constraint (although clearly this also depends on the actions of other countries). The low marginal cost of nuclear electricity means that fuel price increases should have limited impact, allowing exploitation of more expensive alternative uranium sources. However, to mitigate this risk, government policy should be receptive to technological solutions on which its stance is not clear, such as the use of mixed oxide fuel (MOX) in Sizewell B and any new reactors, as well as introduction of 'generation IV' reactors (not considered here).
- The production of nuclear waste requiring geological storage is an intergenerational burden, but should be weighed against the very low carbon footprint of nuclear energy, as well as against nuclear power's alternatives. Coal CCS, for example, produces 74,000 times the volume of waste requiring long-term monitoring. The cost of disposal of such wastes should be borne by the electricity generator: for nuclear power, this is already established in the form of a decommissioning and waste fund (Funded Decommissioning Programme) that the owner must pay into during the plant's operating life; for CCS, arrangements have not been formally defined, but government should ensure that the same policy applies. However, it should be borne in mind that, ultimately, the consumer will pay for any such costs.

10.3 Recommendations for future work

The following topics of research are recommended for future work:

10.3.1 Methodology

1. Extension of the financial incentives indicator to include and appropriately quantify the missing information on hidden subsidies, including allocation of hidden subsidies.
2. Expansion and improvement of the nuclear proliferation indicator, which is presently only a simplified measure designed to be appropriate for current nuclear options.
3. Incorporation of multi-criteria decision analysis (MCDA) into the assessment framework to help identify the most sustainable options based on stakeholder preferences. As discussed in Section 3.2.1.4, total levelised cost should be the only cost indicator used in MCDA in order to avoid double counting; capital, O&M and fuel costs should not be considered separately.

4. Further analysis of alternative LCIA methodologies to CML 2001 (2009 update). This is particularly relevant for human health impacts due to serious disagreement in results between methodologies (see Section 9.1.1.3).
5. Potential extension of the work to allow for 'total' cost estimation (i.e. costing of externalities) to complement the current indicator-led approach.

10.3.2 Assessment of present-day technologies

1. Sustainability assessment of other technologies that are currently operating or may be built in the near future, such as onshore wind, biomass (with and without CCS), natural gas with CCS and marine renewables. This will allow a more complete comparison of technologies.
2. Life cycle assessment (LCA) of specific Generation III+ nuclear plants in a UK setting. This would provide better data which are currently adapted from Generation II plants in Europe.
3. Provision of life cycle inventory data for in-situ uranium mining, as this currently provides over a third of global mined uranium but is not represented in LCA databases despite potentially having significant implications in terms of energy usage and emission of toxic substances to air and groundwater.
4. Incorporation into natural gas LCA of the specific import mix of LNG to the UK in order to make impacts from LNG usage less generic.
5. Refinement of UK coal power LCA via research into the adoption and specification of pollution control measures on UK plants (flue-gas desulphurisation and selective catalytic reduction) as these data are currently unavailable.
6. Refinement of solar PV LCA using currently unavailable data about the UK PV technology mix as opposed to the global average.
7. Research into the employment provided by the decommissioning of power plants, particularly nuclear plants of the types currently being built (LWRs).
8. Research into employment specifically related to natural gas extraction, thereby avoiding the need to allocate data for mixed oil and gas extraction on an economic basis.
9. Further investigation into the availability of employment data specific to Russian coal mining in order to improve accuracy in the coal power life cycle.
10. Improving specificity of employment and worker injury estimates for offshore wind power which are currently constrained by lack of offshore-specific data.
11. Gathering data on employment due directly to solar PV maintenance in the UK in order to improve accuracy; the current estimate is based on modified German data.

12. Probabilistic safety assessment of nuclear plants under UK conditions in order to provide country-specific large accident fatality estimates.
13. Updating estimates of offshore wind farm availability factors by acquiring data for very recent farms in keeping with the high learning rate of the offshore wind sector.

10.3.3 On the assessment of future technologies and scenarios

1. Sustainability assessment of technologies that may be influential in the future, such as Generation IV nuclear plants and floating offshore wind turbines. This will make future scenario analysis more realistic and more comprehensively explore potential impacts.
2. Further refinement of future cost estimates including applying learning rates to individual cost components rather than total levelised cost. This should also include consideration of fossil fuel price projections beyond 2030 in order to estimate more accurately the future costs of coal and gas power.
3. Refinement of LCA modelling of solar PV in future years under UK conditions. This is recommended in order to account more realistically for changes in the technology mix that will occur as thin-film (and other) systems become more common and as panel efficiency improves beyond the 2030 timeframe currently considered by the IEA [see 353].
4. Research into the implications of variable output power sources (such as wind and PV) at levels of deployment likely to occur in the coming decades, as well as their interaction with the rest of the electricity mix. Greater knowledge of energy storage requirements, potential demand-side management and similar technical aspects necessitated by renewable generation will enable more realistic evaluation of the sustainability of renewable-intensive scenarios.

10.4 Concluding remarks

Providing a more sustainable energy supply for the 21st century is a complex challenge. This research demonstrates that the use of sustainability indicators can provide valuable and far-reaching insights into the advantages and disadvantages of different electricity options, both present and future. It is hoped that the assessment methodology and results generated by this study can foster debate and ultimately make a meaningful contribution to energy policy decisions in the UK and abroad.

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12 Appendix 1: Indicators in electricity sector studies

This appendix provides details of the indicators used in each electricity-sector-specific framework considered in the review. In contrast with the discussion in Chapter 2, the indicators are kept in the authors' original groupings.

Afgan & Carvalho, 2008 [32]:

Environment	CO_2 emissions *(kg/kWh)*
Economy	Thermal efficiency *(%)*
	'Cost' *(per kWh)*
	Investment cost *(per kW)*
Society	NO_x emissions *(kg/kWh)*

Begic & Afgan, 2007 [33]:

Environment	CO_2 emissions *(kg/kWh)*
	SO_2 emissions *(kg/kWh)*
	NO_x emissions *(kg/kWh)*
	Resource use *(construction materials, kg/kWh)*
Economy	Thermal efficiency *(%)*
	'Cost' *(per kWh)*
	Investment cost *(per kW)*
Society	Jobs *(hours/kWh)*

Diakoulaki & Karangelis, 2007 [37]:

Environment	CO_2 emissions *(% increase from 1990 levels resulting from each scenario)*
	SO_2 emissions *(kg/yr)*
	NO_x emissions *(kg/yr)*
Economy	Thermal efficiency *(%)*
	Life cycle production cost *(€/MWh)*
	Investment cost *(total, €)*
Technical	Capacity factor *(%)*
	Ability to respond to peak *(qualitative)*
	Security of supply *(qual.)*

Evans et al., 2009 [39]:

No grouping of indicators	GWP *(g CO_2-eq./kWh)*
	Land use *(m^2)*
	Water consumption *(kg/kWh)*
	Thermal efficiency *(%)*
	'Price' *($/kWh)*
	Availability and technology limitations *(qual.)*
	Social impacts *(qual.)*

GRI (Global Reporting Initiative), 2007 [44]:

Environmental	Material use *(total, weight or volume/reporting period)*
	Percentage of recycled input materials *(%)*
	Direct energy consumption, by source *(GJ/reporting period)*
	Indirect energy consumption, by source *(including electricity and heat, GJ/reporting period)*
	Energy saved through efficiency improvements *(GJ/reporting period)*
	Initiatives to provide energy-efficient products *(qual.)*
	Initiatives to reduce indirect energy consumption *(qual.)*
	Total water use *(m^3/yr)*
	Water sources significantly affected by operation *(number, size and biodiversity value)*
	Percentage of water recycled and reused *(%)*
	Land owned in/near sites of high biodiversity *(size, type of operation and biodiversity value)*
	Impact of operations in high biodiversity areas *(qual.)*
	Habitats protected or being restored *(m^2 and status)*
	Strategies for managing impact on biodiversity *(qual.)*
	Number of IUCN Red List species in areas affected by operations *(no.)*
	Total direct and indirect GHG emissions *(t CO_2-eq./MWh)*
	Any other GHG emissions *(t CO_2-eq/MWh)*
	Initiatives to reduce GHG emissions *(qual.)*
	Ozone depletion *(t CFC11-eq./yr)*
	Other air pollutants *(NO_x, SO_x, VOCs etc. in kg/MWh)*
	Total water discharged *(m^3/yr)*
	Total weight of waste *(per MWh)*
	Total number and volume of significant spills *(no. and volume/reporting period)*
	Weight of hazardous waste transported *(kg/yr)*
	Water bodies significantly affected by discharges and run-off *(qual.)*
	Initiatives to reduce impact of products *(qual.)*
	Percentage of products and packaging reclaimed for recycling/reuse *(%)*
	Fines for breaching environmental regulations *(monetary units/reporting period)*
	Environmental impacts of transport *(qual.)*
	Expenditure in environmental protection *(monetary units/reporting period)*
Economic	Direct economic value generated *(monetary units/reporting period)*
	Financial implications of climate change *(qual.)*
	Benefit plan obligations *(qual.)*
	Financial assistance from government *(monetary units/reporting period)*
	Ratio of entry-level wage to national minimum wage *(ratio)*
	Proportion of spending on local suppliers *(%)*
	Proportion of senior management hired from local community *(%)*
	Impact of investments on local infrastructure *(qual.)*
	Understanding and describing significant indirect economic impacts *(evidence that the organisation investigates its impacts, qual.)*
Social: Labour Practices & Decent Work	Total size of workforce *(no. employees)*
	Percentage of contractors that have undergone safety training *(%)*
	Employee turnover *(no./yr)*
	Benefits provided *(qual.)*
	Employees covered by collective bargaining agreements *(inc. contractors, %)*
	Minimum notice period regarding significant changes in operation *(weeks)*

	Employees represented by a formal health and safety committee *(%)*
	Rates of injury, absenteeism and fatality *(inc. contractors, per yr)*
	Education etc. regarding serious disease *(qual.)*
	Formal agreements with trade unions on health and safety *(qual.)*
	Training *(average hours/yr/employee)*
	Programmes to assist leaving employees *(qual.)*
	Employees receiving regular performance reviews *(%)*
	Composition of workforce *(by gender, ethnicity, age group)*
	Equal pay *(ratio of basic salary of men to women, by group)*
Social: Human Rights	Percentage of investment agreements including human rights clauses *(%)*
	Percentage of significant suppliers/contractors undergoing human rights screening *(%)*
	Total hours of employee training on human rights related policies *(hrs/yr and % employees trained)*
	Number of discrimination incidents and actions taken *(no./reporting period)*
	Impingement of workers' right to freedom of association *(qual.)*
	Operations involving a risk of child labour *(qual.)*
	Operations involving a risk of forced labour *(qual.)*
	Percentage of security personnel trained in human rights *(%)*
	Number of indigenous peoples' rights violations and actions taken *(no./reporting period)*
Social: Society	Presence of programs that assess/manage community impacts *(qual.)*
	Percentage of business units assessed for risk of corruption *(%)*
	Percentage of employees trained in anti-corruption policies *(%)*
	Actions taken in response to incidents of corruption *(qual.)*
	Participation in government policy-forming activities and lobbying *(qual.)*
	Total value of contributions to political parties or politicians *(€/reporting period)*
	Total number of legal actions for anti-competitive, anti-trust or monopoly behaviour *(no./reporting period)*
	Monetary value of fines/sanctions for non-compliance with regulations *(€/reporting period)*
Social: Product Responsibility	Percentage of life cycle stages assessed for health and safety improvements *(%)*
	Number of incidents of product non-compliance with health and safety codes *(inc. injuries to the public, no./reporting period)*
	Type of product information given to consumers *(qual.)*
	Number of incidents of product non-compliance with labelling codes *(no./reporting period)*
	Practices related to customer satisfaction *(qual.)*
	Adherence to standards or voluntary codes related to marketing *(qual.)*
	Number of incidents of product non-compliance with marketing codes *(no./reporting period)*
	Number of complaints related to breaches of customer privacy *(no./reporting period)*
	Total value of fines due to non-compliance with regulations *(€/reporting period)*
	Percentage of population unserved in distribution area *(%)*
	Number of residential disconnections for non-payment *(no./reporting period)*
	Power outage frequency *(System Average Interruption Frequency Index (SAIFI))*
	Power outage duration *(System Average Interruption Duration Index (SAIDI))*
	Average plant availability factor *(%)*

Haldi & Pictet, 2003 [35]:

Health & Environment	GWP *(kg CO_2-eq./kWh)*
	Resource consumption *(energetic only, % global reserves)*
	Waste: total *(tons/GWh)*
	Waste: approximate confinement time *(yrs)*
	Land use *(km^2/GWh degraded from one type to another)*
	Health impact due to accidents: expected fatalities *(per GWh)*
	Health impact due to accidents: maximum credible number of fatalities *(per GWh)*
Economy	Average cost *(yuan/kWh)*
	Total investment cost *(yuan)*
	Fuel transport burden *(% increase in fuel transportation by 2020)*
Society	Employment *(direct only: net number of jobs × time × salary = yuan/GWh)*
Technology	Maturity *(qual.)*

Hirschberg et al., 2004 [40]:

Environment	GWP *(tons CO_2-eq./GWh)*
	Regional impact *(change in unprotected ecosystem area, km^2/GWh)*
	Land use *(m^2/GWh)*
	Fatalities due to severe accidents *(fatalities/GWh)*
	Total waste production *(tons/GWh)*
Economy	Production cost *(c/kWh)*
	Fuel price increase sensitivity *(increase in production cost due to a doubling of fuel prices)*
	Availability factor *(%)*
	Geopolitical factors *(qual.)*
	Long-term sustainability: energetic *(yrs of global supply remaining)*
	Long-term sustainability: non-energetic *(kg/GWh)*
	Peak load response *(qual.)*
Social	Employment *(technology-specific: person-years/GWh)*
	Proliferation potential *(qual.)*
	Human health impacts from normal operation *(years of life lost/GWh)*
	Local disturbance *(noise and visual amenity, qual.)*
	Necessary confinement time of waste *(thousands of yrs)*
	Risk aversion *(max. credible no. fatalities per accident)*

Khan et al., 2004 [42]:

Environment & Resources	Resource consumption *(energy sources, materials and renewables, kg/kWh)*
	GHG emissions *(kg CO_2-eq./kWh)*
	Ozone depletion *(kg CFC12-eq./kWh)*
	Acidification [56]
	Oxidation *(kg O_3-eq./kWh)*
	Mass of air pollutant released *(kg/kWh)*
	Mass of water pollutant released *(kg/kWh)*
	Mass of solid waste released *(kg/kWh)*
	Human health risk *(cumulative hazard quotient)*
	Ecological risk *(cumulative hazard index)*
	Safety risk *(potential fatalities/yr)*
Cost	Fixed cost *(initial capital, $/kWh)*
	Operating cost *($/kWh)*

	Health, safety and environmental costs *($)*
Socio-political	Acceptance *(qual.)*
	Vulnerability of area *(risk of earthquake, annual rainfall, average windspeed, risk of riot)*
	Social impacts *(qual.)*
Technology	Feasibility *(qual.)*
	Extreme process conditions *(highest temperature and pressure)*
	Energy efficiency *(kWh consumed/kWh produced)*
	Human-machine interaction *(% time machines are used)*

Kowalski et al., 2009 [36]:

No grouping of indicators	Climate change properties *(t CO_2-eq./TJ)*
	Stratospheric ozone *(kg O_3/TJ)*
	Dust *(kg/TJ)*
	Air quality - acidification *(kg SO_2-eq./TJ)*
	Air quality - TOPP *(kg/TJ)*
	Air quality - particulate matter *(kg/TJ)*
	Cumulative energy input *(GJ/TJ)*
	Cumulative material input *(kg/TJ)*
	Sealed land *(m^2)*
	Water quality - phosphorus *(mg/TJ)*
	Water quality - nitrogen *(g/TJ)*
	Water quality - AOX *(mg/TJ)*
	Water quality - CSB *(kg/TJ)*
	Water quality - BSB *(g/TJ)*
	Cost *(€/TJ)*
	Import dependency *(%)*
	Employment *(no. of people)*
	Regional self-determinacy *(qual.)*
	Social cohesion *(qual.)*
	Diversity of technology *(qual.)*
	Effect on public spending *(qual.)*
	Quality of landscape *(qual.)*
	Noise *(qual.)*
	Smell *(qual.)*
	Social justice *(qual.)*
	Technological advantage *(qual.)*
	Ecological justice *(qual.)*
	Security of supply *(qual.)*
	Effect on water habitats *(qual.)*
	Effect on soil habitats *(qual.)*
	Empowerment *(qual.)*
	Regional economic development *(qual.)*
	Diversity *(qual.)*
	Adaptability *(qual.)*
	Quality of landscape *(qual.)*

May & Brennan, 2006 [46]:

Environmental	Resource depletion - world *(CML method, kg Sb-eq./MWh)*
	Resource depletion - Australia *(CML method, kg Sb-eq./MWh)*
	Resource depletion - Energy use *(MJ/MWh)*
	Resource depletion - Exergy destruction *(MJ/MWh)*
	GHG emissions *(kg CO_2-eq./kWh)*
	Acidification *(kg SO_2-eq./MWh)*
	Photochemical smog *(kg ethylene-eq./MWh)*
	Eutrophication *(kg PO_4-eq./MWh)*
	Solid waste production *(kg/MWh)*
Economic	Capital cost *($Aus)*
	Value added *($Aus)*
	Capital-inclusive value added *($Aus)*
	Annualised cost *(Aus$/yr)*
Social	Direct employment *(no. employees)*
	Indirect employment *(estimated no. employees)*
	Lost-time injuries *(lost days due to injury per million work hours)*
	Fatalities *(reported no./yr)*

NEA (Nuclear Energy Agency), 2007 [45]:

Environmental	GHG emissions *(tons CO_2-eq./kWh)*
	SO_2 emissions *(kg/kWh)*
	NO_x emissions *(kg/kWh)*
	PM^{10} emissions *(kg/kWh)*
	Solid waste production: non-radioactive *(kg/kWh)*
	Solid waste production: radioactive *(m^3/kWh)*
	Land use *(m^2/kWh)*
	Accident risks *(fatalities/GWyr and probabilistic safety assessment)*
Economic	Generation costs *(€/MWh)*
	Fuel price increase sensitivity *(increase in production due to a doubling of fuel prices)*
	Availability factor *(%)*
	Security of fuel supply *(qual. assessment of geopolitical factors)*
	Lifetime of fuel resources *(yrs of global supply remaining)*
	Use of energy resources *(fossil fuel use, MJ/kWh)*
	Use of non-energetic resources *(kg Cu/kWh)*
Social	Employment *(qual.)*
	Human health impacts from normal operation *(years of life lost/GWh)*
	Necessary confinement time of waste *(qual.)*
	Proliferation risk *(qual.)*
	Risk aversion *(max. credible no. fatalities per accident)*

NEEDS (New Energy Externalities Development for Sustainability), 2008 [34]:

Environmental	Total consumption of fossil resources *(MJ/kWh)*
	Total consumption of uranium *(MJ/kWh)*
	Weighted total consumption of metallic ores *(kg Sb-eq./kWh)*
	Global warming potential *(kg CO_2-eq./kWh)*
	Impacts of land use on ecosystems *(PDF*m^2*a/kWh)*
	Impacts of toxic substances on ecosystems *(PDF*m^2*a/kWh)*

	Impacts of air pollution on ecosystems *(PDF*m^2*a/kWh)*
	Large release of hydrocarbons *(t/kWh)*
	Nuclear land contamination *(km^2/kWh)*
	Total weight of special chemical wastes stored in underground repositories *(kg/kWh)*
	Total amount of ILW and HLW to be stored in geological repositories *(m^3/kWh)*
Economic	Average generation costs *(€/MWh)*
	Direct labour *(person-years/GWh)*
	Medium to long-term independence from foreign energy sources *(ordinal scale)*
	Total capital cost *(€)*
	Ratio of the fuel cost to the generation cost *(fraction)*
	Construction time *(years)*
	Total average variable cost or 'dispatch cost' *(€/MWh)*
	Flexibility of dispatch composite indicator *(ordinal scale)*
	Equivalent availability factor *(fraction)*
Social	Diversity of primary energy suppliers (market concentration) *(ordinal scale.)*
	Probability that waste storage management will not be available *(ordinal scale)*
	Flexibility to incorporate technological change *(ordinal scale)*
	Potential of energy system induced conflicts *(ordinal scale)*
	Willingness of NGOs and other citizen movements to act against realisation of an option *(ordinal scale)*
	Necessity of participative decision-making processes for different technologies *(ordinal scale)*
	Mortality due to normal operation *(YOLL/kWh)*
	Morbidity due to normal operation *(DALY/kWh)*
	Expected mortality due to severe accidents *(fatalities/kWh)*
	Maximum credible number of fatalities per accident *(fatalities/accident)*
	Subjective health fears due to normal operation *(ordinal scale)*
	Psychometric variables such as personal control, catastrophic potential, perceived equity, familiarity *(ordinal scale)*
	Potential for a successful terrorist attack *(ordinal scale)*
	Expected number of fatalities in terrorist attack *(ordinal scale)*
	Potential for misuse of technologies and substances within the nuclear energy chain *(ordinal scale)*
	Share of the effective electricity costs in the budget of a social welfare recipient *(%)*
	Work qualifications expressed as average years of education for workforce *(ordinal scale)*
	Functional and aesthetic impact of energy infrastructure on landscape *(ordinal scale)*
	Extent to which residents feel highly affected by noise *(ordinal scale)*
	Total traffic load *(tkm/kWh)*

Polatidis and Haralambopoulos, 2007 [43]:

Environmental	CO_2 reduction potential *(tons CO_2 avoided)*
	Land use *(m^2)*
	Compatibility with other activities *(qual.)*
	Noise creation *(dB increase × no. people affected)*
	Visual impact *(qual.)*
	Electricity networks and access roads *(km of new network and road added)*
Economic	Return on investment *(payback period of initial cost, yrs)*
	Net Present Value *(€)*
	Installation cost *(€/kW)*

	Operational cost *(€/kWh)*
	Community economic benefit *(direct payments, €/yr)*
	Entrepreneurial risk *(qual.)*
Social	Employment *(man-days/yr)*
	Public acceptance *(qual.)*
Energy & Resource Use	Amount of imported oil avoided *(tons oil-eq./yr)*
	Amount of electricity produced *(kWh/yr)*
Technological	Reliability and safety *(qual.)*

Roth et al., 2009 [41]:

Environmental	Use of fossil energy *(units not given)*
	Use of uranium *(units not given)*
	Use of metals *(units not given)*
	Climate change *(units not given)*
	Land use *(units not given)*
	Ecotoxicity *(units not given)*
	Acidification and eutrophication *(units not given)*
	Land contamination *(units not given)*
	Non-radioactive waste production *(units not given)*
	Radioactive waste production *(units not given)*
Economic	Contribution to the national economy *(units not given)*
	Jobs in Alpine regions *(units not given)*
	Jobs in non-Alpine regions *(units not given)*
	New jobs in non-Alpine regions *(units not given)*
	Qualification of employees *(units not given)*
	Education of employees *(units not given)*
	Jobs in R&D *(units not given)*
	Technology transfer *(units not given)*
	Development of new products/services *(units not given)*
	Effect on electricity cost *(units not given)*
	Autonomy of electricity production *(units not given)*
	Cash flow to the state *(units not given)*
	External costs and benefits *(units not given)*
	Profits *(units not given)*
	Volatility of fuel costs *(units not given)*
	Risks due to authorities' interventions *(units not given)*
	Necessary measures in advance and after operation *(units not given)*
	Operator liquidity *(units not given)*
	Time for construction of the plant *(units not given)*
	Flexibility based on marginal costs *(units not given)*
	Flexibility of production *(units not given)*
	Limitations in electricity production *(units not given)*
	Predictability of energy availability *(units not given)*
	Technical site availability *(units not given)*
	Impacts on image of operator *(units not given)*
	Compatibility with Axpo's corporate culture *(units not given)*
Social	Terrorist threat – maximum number of fatalities *(units not given)*
	Terrorist threat – loss of production *(units not given)*

	Terrorist threat – cost of reconstruction *(units not given)*
	Availability of disposal infrastructure *(units not given)*
	Availability of disposal concept *(units not given)*
	Potential of conflicts – mobilisation *(units not given)*
	Potential of conflicts – post-operational safeguarding *(units not given)*
	Potential of conflicts – proliferation *(units not given)*
	Potential of conflicts – conflicts over resources *(units not given)*
	Existence of conflict resolution mechanism *(units not given)*
	Trust in utility *(units not given)*
	Qualitative risk characteristics *(units not given)*
	Participation of residents *(units not given)*
	Socio-economic image *(units not given)*
	Impacts on local infrastructure *(units not given)*
	Satisfaction of residents *(units not given)*
	Fair distribution of risks and benefits *(units not given)*
	Electricity for economically weak groups *(units not given)*
	Noise impact on residents *(units not given)*
	Site dependent traffic *(units not given)*
	Impulses for sustainable utility behaviour *(units not given)*
	Impulses for sustainable consumer behaviour *(units not given)*
	Quality of landscape – direct land use *(units not given)*
	Quality of landscape – aesthetic impacts *(units not given)*
	Normal operation – mortality *(units not given)*
	Normal operation – morbidity *(units not given)*
	Severe accidents – fatalities *(units not given)*
	Severe accidents – injuries *(units not given)*
	Severe accidents – evacuees *(units not given)*
	Perceived health risks (normal operation) *(units not given)*
	Perceived health risks (accidents) *(units not given)*
	Perceived safety management competence *(units not given)*
	Overexploitation of renewable resources *(units not given)*

13 Appendix 2: Definition and estimation of indicators

13.1 Techno-economic indicators

13.1.1 Operability: capacity factor; availability; dispatchability; fuel reserves

Capacity factor is the power output of a plant in a specified time expressed as a percentage of the maximum possible power output over the same time period had the plant been running continuously at full power:

$$CF = \frac{P_{\text{out}}}{P_{\max}} \times 100 \quad (\%)$$

CF – capacity factor (%)
P_{out} – power output of a plant (MWh)
P_{max} – maximum possible power output (MWh)

Availability is the percentage of time that a plant is available to produce electricity and is calculated as follows:

$$A = \frac{t_A}{t_{\max}} \times 100 \quad (\%)$$

A – plant availability (%)
t_A – time over which the plant is available for generation of electricity over one year (hrs/yr)
t_{max} – maximum operating time over one year (hrs/yr)

Dispatchability is the ability of a generating unit to increase or decrease generation, or to be brought on line or shut down as needed. Two types of dispatchability are distinguished here: *technical* and *economic*.

Technical dispatchability: ramp-up rate; ramp-down rate; minimum up time; minimum down time

Ramp-up rate:

$$RU = \frac{RU_{\max}}{P_{\max}} \times 100 \quad (\%)$$

RU – ramp-up rate (%)
RU_{max} – maximum rate of power increase (MW/min)
P_{max} – maximum power output (MW)

Ramp-down rate:

$$RU = \frac{RU_{\max}}{P_{\max}} \times 100 \quad (\%)$$

RD – ramp-down rate (%)
RD_{max} – maximum rate of power decrease (MW/min)
P_{max} – maximum power output (MW)

Minimum up time: minimum time for which a unit must operate at power before being shut down.

Minimum down time: minimum time for which a unit must remain shut down before returning to power.

The overall technical dispatchability is estimated by ranking the electricity-generating technologies on each of the four technical-dispatchability criteria defined above and then summing the rankings to derive a total technical dispatchability value:

$$TD = R_{RUR} + R_{RDR} + R_{MUT} + R_{MDT} \quad (-)$$

TD – technical dispatchability value (-)
R_{RUR} – ranking for ramp-up rate
R_{RDR} – ranking for ramp-down rate
R_{MUT} – ranking for minimum up time
R_{MDT} – ranking for minimum down time

Economic dispatchability is the ratio of capital to total levelised electricity costs (for the estimation of the latter, see further below):

$$ED = \frac{CC}{LEC} \quad (-)$$

ED – economic dispatchability (-)
CC – capital component of total levelised costs (pence/kWh)
LEC – levelised electricity costs (pence/kWh)

Lifetime of fuel reserves represents a ratio of economically recoverable resources and the current rate of usage of fuel reserves:

$$LFR = \frac{ERR}{UR} \quad \text{(years)}$$

LFR – lifetime of fuel reserves (years)
ERR – economically recoverable resources (t)
UR – current usage rates of fuels (t/yr)

13.1.2 Technological lock-in

This indicator is defined by two parameters, lifespan and flexibility, and is estimated as:

$$T = \frac{f^2}{l} \quad (years^{-1})$$

T - technological lock-in score ($years^{-1}$)
f - flexibility index (0-30)
l - lifespan of the technology (years)

The flexibility index is related to the ability of a technology for trigeneration, negative CO_2 emissions and H_2 production. Each of these three options is allocated 10 points, so that *f* ranges from 0-30.

13.1.3 Levelised electricity cost

This indicator expresses the cost of generating electricity, throughout the full life cycle of a power plant, discounted at an appropriate rate. It is calculated as:

$$LEC = \frac{\sum_{n=1}^{N} \frac{CC_t + M_t + F_t}{(1+r)^t}}{\sum_{n=1}^{N} \frac{E_t}{(1+r)^t}} \times 10^{-2} \quad \text{(p/kWh)}$$

LEC – levelised electricity cost (p/kWh)
CC_t – capital costs (investment) in year *t* (£)
M_t - operations and maintenance expenditure in year *t* (£)
F_t - fuel expenditure in year *t* (£)
E_t - electricity generation in year *t* (kWh)
r - discount rate
N – lifetime of the power plant

13.1.4 Cost variability: fuel price sensitivity

This indicator represents the ratio of fuel cost to total levelised generation cost:

$$CV = \frac{FC}{LEC} \quad (-)$$

CV – fuel cost variability (fuel price sensitivity) (-)
FC – fuel cost (p/kWh)
LEC – levelised electricity costs (p/kWh)

13.2 Environmental indicators

13.2.1 Material recyclability

This indicator estimates the proportion of a power plant that is recycled at the end of its lifetime as follows:

$$MR = \frac{\sum_{j}^{J} R_j}{M_p} \times 100 \quad (\%)$$

MR – overall material recyclability (%)
R_i – amount of material *j* that can be recycled (t)
M_p – total amount of materials contained in the power plant (t)

13.2.2 Water eco-toxicity: Freshwater and marine eco-toxicity potential

These two indicators are based on the maximum tolerable concentrations of toxic substances by different organisms in the freshwater and marine environments. The reference substance is 1,4-dichlorobenzene (DCB) and the indicators are calculates as:

$$FWETP = \sum_{j=1}^{J} FWETP_j \times B_j$$
(kg 1,4-DCB eq./kWh)

FWETP – total freshwater eco-toxicity potential of energy technology
(kg 1,4-DCB eq./kWh)
$FWETP_j$ – freshwater eco-toxicity potential of substance *j*
(kg 1,4-DCB eq./kg)

$$METP = \sum_{j=1}^{J} METP_j \times B_j$$
(kg 1,4-DCB eq./kWh)

METP – total marine eco-toxicity potential of energy technology (kg 1,4-DCB eq./kWh)
$METP_j$ – marine eco-toxicity potential of substance *j* (kg 1,4-DCB eq./kg)
B_j – emission of substance *j* to freshwater or seawater (kg/kWh)
J – total number of toxic species

13.2.3 Global Warming Potential

Global warming potential (GWP) expresses the potential of different greenhouse gases (GHGs) to cause climate change. GWP factors for different GHGs are expressed relative to the GWP of CO_2, which is defined as unity. It is calculated as:

$$GWP = \sum_{j}^{J} GWP_j \times B_j \quad (\text{kg } CO_2 \text{ eq./kWh})$$

GWP – total GWP of energy technology (kg CO_2 eq./kWh)
GWP_j – GWP factor for GHG *j* (kg CO_2 eq./kg)
B_j – emission of GHG *j* (kg/kWh)
J – total number of GHGs

The values of GWP depend on the time horizon over which the global warming effect is assessed. GWP factors for shorter times (20 and 50 years) provide an indication of the short-term effects of greenhouse gases on the climate, while GWP for longer periods (100 and 500 years) are used to predict the cumulative effects of these gases on the global climate. GWP100 is used more widely and therefore within this framework.

13.2.4 Ozone Layer Depletion Potential

Ozone layer depletion potential (ODP) indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and other halogenated hydrocarbons to deplete the ozone layer. It is expressed relative to the ozone depletion potential of CFC-11 and calculated as:

$$ODP = \sum_{j}^{J} ODP_j \times B_j \quad (\text{kg CFC-11 eq./kWh})$$

ODP – total ozone layer depletion potential of energy technology (kg CFC-11 eq./kWh)
ODP_j – ODP of ozone depleting gas *j* (kg CFC-11 eq./kg)
B_j – emission of ozone depleting gas *j* (kg/kWh)
J – total number of ozone depleting substances

13.2.5 Acidification potential

Acidification potential (AP) expresses the contribution of sulphur dioxide (SO_2), nitrogen oxides (NOx) and ammonia (NH_3) to acid rain and related impacts. It is expressed relative to the AP of SO_2 and calculated according to the equation:

$$AP = \sum_{j}^{J} AP_j \times B_j \quad \text{(kg SO}_2\text{ eq./kWh)}$$

AP – overall acidification potential of energy technology (kg SO_2 eq./kWh)
AP_j – acidification potential of acid gas *j* (kg SO_2 eq./kg)
B_j – emission of acid gas *j* (kg/kWh)
J – total number of acid gases

13.2.6 Eutrophication potential

Eutrophication potential (EP) is defined as the potential of nutrients such as N, NOx, NH_4^+, PO_4^{3-} and P to cause over-fertilisation of water and soil, which can result in increased growth of biomass (algae). It is expressed relative to PO_4^{3-} and calculated as:

$$EP = \sum_{j}^{J} EP_j \times B_j \quad \text{(kg PO}_4^{3-}\text{ eq./kWh)}$$

EP - overall eutrophication potential of energy technology (kg PO_4^{3-} eq./kWh)
EP_j – eutrophication potential of nutrient *j* (kg PO_4^{3-} eq./kg)
B_j – emission of nutrient *j* (kg/kWh)
J – total number of nutrients

13.2.7 Photochemical oxidant creation potential (summer smog)

This indicator is related to the potential of Volatile Organic Compounds (VOCs) and nitrogen oxides (NOx) to generate photochemical or summer smog. It is usually expressed relative to the photochemical ozone creation potential (POCP) of ethylene and can be calculated as:

$$POCP = \sum_{j}^{J} POCP_j \times B_j \quad \text{(kg C}_2\text{H}_4\text{ eq./kWh)}$$

POCP – total photochemical oxidant creation potential of energy technology (kg ethylene eq./kWh)
$POCP_j$ – POCP potential of species *j* (kg C_2H_4 eq./kg)
B_j – emission of substances *j* contributing to the formation of summer smog (kg/kWh)
J – total number of substances contributing to the formation of summer smog

13.2.8 Land use and quality: Impacts of land use; greenfield land use; terrestrial eco-toxicity

Impact of land use (ILU) is calculated as:

$$ILU = A \times t \quad \text{(m}^2\cdot\text{yr/kWh)}$$

ILU – total impact of energy technology on land use over time ($m^2 \cdot yr$/kWh)
A – land area occupied (m^2)
t – time over which land is occupied (yr)

Greenfield land use is expressed as the percentage of the area of greenfield land that needs to be converted for the construction of power plant, relative to the total amount of area that will be occupied by the plant. It is calculated as:

$$GF = \frac{GFA}{TLA} \times 100 \quad (\%)$$

GF – percentage of greenfield land used for construction of power plant (%)
GFA – area of greenfield land used (m^2)
TLA – total land area occupied by the power plant (m^2)

Terrestrial eco-toxicity potential (TETP) is based on the maximum tolerable concentrations of toxic substances by different organisms in terrestrial environment. The reference substance is 1,4-dichlorobenzene and it is calculates as:

$$TETP = \sum_{j=1}^{J} TETP_j \times B_j \quad \text{(kg 1,4-DCB eq./kWh)}$$

TETP – terrestrial eco-toxicity potential of energy technology (kg 1,4-DB eq./kWh)
$TETP_j$ – terrestrial eco-toxicity potential of toxic substance *j* (kg 1,4-DB eq./kg)
B_j – emission of substance *j* to land (kg/kWh)
J – total number of toxic substances emitted to land

13.3 Social indicators

13.3.1 Employment provision: direct and total

This indicator measures employment provision in the life cycle of an energy technology. It is expressed in person-yrs per total amount of electricity generated over the life time of energy technology.

Direct employment measures number of person-yrs/GWh directly employed in the life cycle of energy technology and is calculated as follows:

$$DE = \frac{\sum_{i=1}^{I} DE_i \times t_i}{P_{tot}} \quad \text{(person-yrs/GWh)}$$

DE – direct employment provision over the life cycle of an energy technology (person-yrs/GWh)
DE_i – direct employment provision in life cycle stage *i* (no. of people employed)
t_i – duration of employment in life cycle stage *i* (yrs)
P_{tot} – total amount of energy generated over the lifetime of energy technology (GWh*)
I – total number of life cycle stages
(*GWh rather than kWh to avoid small numbers)

Indirect employment is related job creation owing to the activities related to electricity provision and is calculated in the same way as DE.

Total employment represents the sum of direct and indirect employment: DE = DE + IE (person-yrs/GWh).

13.3.2 Human health impacts: worker injuries; human toxicity potential (excluding radiation); human health impacts from radiation (workers and population)

Worker injuries represents the total number of worker deaths, major and minor injuries (causing more than three days absence from work) per unit of electricity generated in the whole life cycle of electricity generation and is calculated as:

$$WI = \sum_{i=1}^{I} E_i \times r_i \quad \text{(injuries/GWh)}$$

WI – total number of worker injuries (injuries/GWh)
E_i – employment in life cycle stage *i* (person-yrs/GWh)
r_i – average annual injury rate for the sector appropriate to life cycle stage *i* (injuries/worker)

Human toxicity potential (HTP) is calculated by taking into account releases toxic to humans to three different media, i.e. air, water and soil:

$$HTP = \sum_{j}^{J} HCA_{Aj} \times B_{Aj} + \sum_{j}^{J} HCW_{Wj} \times B_{Wj} + \sum_{j}^{J} HCS_{Sj} \times B_{Sj} \quad \text{(kg 1,4-DCB eq./kWh)}$$

HTP_{Aj}, HTP_{Wj}, *and* HTP_{Sj} – toxicological potentials for substances emitted to air, water and soil, respectively (kg 1,4 DCB eq./kg)
B_{Aj}, B_{Wj} *and* B_{Sj} – emissions of different toxic substances into the three environmental media (kg/kWh)
J – total number of substances toxic to humans

Human health impacts from radiation (HIR): This indicator is divided in two indicators to distinguish between the impacts from radiation on workers and total impact on workers and general population. Both indicators are expressed in terms of disability-adjusted life years (DALY) lost due to the effects of radiation. This includes the years of life lost due to cancer and hereditary disease as well as the years in which individuals live with disease/disability. The severity of each disease is based on evaluations by a panel of health experts using a scale from 0-1, where '0' is perfect health and '1' is death. HIR is calculated as follows:

$$HIR = \frac{\sum_{d}^{D} YL_d + D_d S_d}{P_{tot}} \quad \text{(DALY/GWh)}$$

HIR – human health impacts from radiation (DALY/GWh)
YL_d –life lost due to disease *d* (yr)
D_d – average duration of disease *d* (yr)
S_d – average severity of disease *d*, as estimated by health experts (0-1)
P_{tot} – total amount of energy generated over the lifetime of energy technology (GWh)

13.3.3 Large accident risk

This indicator measures the number of fatalities due to large accidents over the life cycle of electricity generation and is expressed per unit of electricity generated as follows:

$$LAR = \sum_{i}^{I} LAR_i \quad \text{(no./GWh)}$$

LAR – total number of fatalities (no./GWh)
LAR_i – number of worker fatalities in life cycle stage *i* per GWh electricity produced (no./GWh)
I – total number of life cycle stages

13.3.4 Local community impacts: proportion of staff hired from local community; proportion of spending on local suppliers; and direct investment in local community

Proportion of staff hired from local community is expressed relative to the total provision of direct employment during the operation stage of a power plant. It is calculated as follows:

$$P_{LS} = \frac{LS}{DEO} \times 100 \quad (\%)$$

P_{LS} – proportion of staff hired from local community during the operation stage of a power plant (%)
LS – number of staff hired from local community per unit of electricity generated during the operational lifetime of a power plant (person-yrs/GWh)
DEO – total number of staff directly employed per unit of electricity generated during the operational lifetime of a power plant (person-yrs/GWh)

Proportion of spending on local suppliers is expressed relative to the total spend each year:

$$P_{LSUP} = \frac{S_{LSUP}}{S_{tot}} \times 100 \quad (\%)$$

P_{LSUP} – proportion of spending on local suppliers each year (%)
S_{LSUP} – annual spend on local suppliers (£/yr)
S_{tot} – total annual spend related to the operation and maintenance of the plant (£/yr)

Direct investment in local community is expressed as percentage investment relative to the total annual revenue:

$$P_{LDI} = \frac{LDI}{R_{tot}} \times 100 \quad (\%)$$

P_{LDI} – proportion of direct investment in local community each year (%)
LDI – annual investment in local community (£/yr)
R_{tot} – total annual revenue (£/yr)

13.3.5 Human rights and corruption

This indicator is calculated as an average Corruption Perceptions Index (CPI) [154] of the countries involved in the life cycle of an energy system:

$$CPI = \frac{\sum_{c}^{C} CPI_c}{C} \quad \text{(Score 0-10)}$$

CPI – average corruption perceptions index (Score 0-10)
CPI_c – corruption perceptions index for country *c* in the life cycle of an energy technology
C – total number of countries

13.3.6 Energy security: imported fossil fuel avoided; diversity of fuel supply; fuel storage capacity

Imported fossil fuel avoided
This indicator measures the amount of imported fossil fuel potentially avoided by non-fossil fuel electricity generating technologies, calculated as follows:

$$IFA = \frac{100}{\eta_a} \times K \quad \text{(koe/kWh)}$$

IFA – imported fossil fuel potentially avoided (koe/kWh)
η_a – average efficiency of the fossil fuel fleet (%)
K – conversion for kilowatt-hour to kilograms oil equivalent (koe/kWh)

Diversity of fuel supply (DFS) mix is based on the proportions of national fuel supply imported and exported, where the import mix is assessed for diversity using the Simpson Diversity Index (SID). It is calculated as follows:

$$DFS = P_{in} + P_{im}\left(1 - \frac{\sum_{c}^{C} n_c(n_c - 1)}{9900}\right)$$

(Score 0-1)

P_{in} – proportion of national fuel demand produced indigenously
P_{im} – proportion of national fuel demand imported
n_c – percentage of fuel imports supplied by exporting country *c*

Fuel storage capability addresses the ease with which fuel can be stored. For conventional fuels, it is simply the net calorific value of the fuel (GJ/m^3). In the case of nuclear power, the relevant criterion is the energy density per fuel assembly volume rather than per uranium volume. This can be calculated as:

$$ED = \frac{MA_u \times BU}{VA_{tot}} \quad \text{(GJ/m}^3\text{)}$$

ED – volumetric energy density of nuclear fuel (GJ/m^3)
MA_u – mass of uranium in one fuel assembly (t) BU – assumed 'burn-up' of uranium in fuel (GJ/tU)
VA_{tot} – total volume of one fuel assembly (t)

13.3.7 Intergenerational equity: abiotic resource depletion; long-term storage of hazardous waste

Abiotic resource depletion potential (ADP) represents depletion of fossil fuels and minerals. It is expressed in Mj/kWh and kg Sb/kWh, respectively for fossil fuels and minerals. The total impact is calculated as:

$$ADP_F = \sum_{j}^{J} ADP_{Fj} \times B_{Fj} \quad \text{(MJ/kWh)}$$

ADP_F – abiotic resource depletion potential for fossil fuels (MJ/kWh)
ADP_{Fj} – abiotic depletion potential for fossil fuel *j* (MJ/kg)
B_{Fj} – quantity of fossil fuel *j* used (kg/kWh)

ADP_M – abiotic resource depletion potential for minerals (kg Sb eq./kWh)
ADP_{Mj} – abiotic depletion potential for mineral *j* (kg Sb eq./kg)

$$ADP_M = \sum_j^J ADP_{Mj} \times B_{Mj}$$

(kg Sb eq./kWh)

B_{Mj} – quantity of mineral *j* used (kg/kWh)

Long-term storage of hazardous waste represents the long-term waste monitoring burden resulting from nuclear power and carbon capture and storage (CCS). Nuclear waste is normally expressed volumetrically, whereas CO_2 is normally expressed in mass terms and therefore requires conversion to storage volume as described below.

$$LSW_{NUC} = \sum_i^I w_i \quad (\text{m}^3/\text{kWh})$$

LSW_{NUC} – Long-term storage of nuclear waste (m^3/kWh)
w_i – quantity of nuclear waste destined for geological disposal produced in life cycle stage *i* (m^3/kWh)

$$LSW_{CAR} = \frac{\sum_i^I c_i}{d} \quad (\text{m}^3/\text{kWh})$$

LSW_{CAR} – Long-term storage of supercritical carbon dioxide from CCS (m^3/kWh)
c_i – quantity of carbon dioxide removed for long-term storage in life cycle stage *i* (kg/kWh)
d – density of carbon dioxide under supercritical conditions at storage site (kg/m^3)

14 Appendix 3: Indicator results, present day, by technology

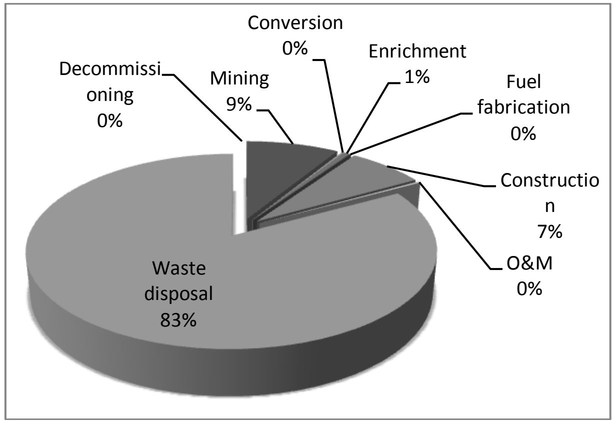
14.1 Nuclear power

14.1.1 Techno-economic results

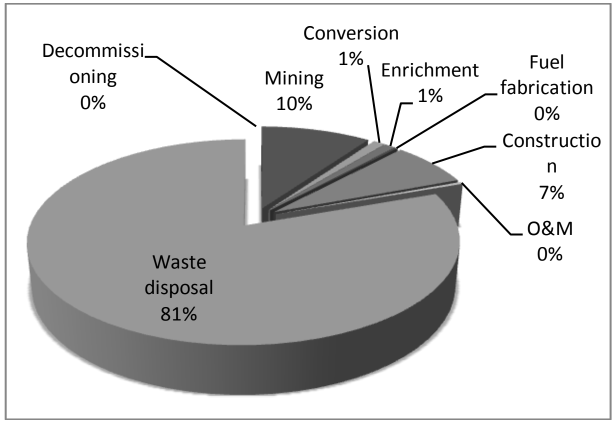
	Nuclear (PWR)		
	Min.	**Central**	Max.
1. Capacity factor (%)	49.40	85.00	90.00
2. Availability factor (%)	50.67	89.21	92.70
3. Technical dispatch. (no units)	11.00	11.67	12.00
4. Economic dispatch. (no units)	54.23	79.28	83.93
5. Lifetime of fuel reserves (yrs)	25.00	80.00	675.00
6. Technological lock-in resistance (yrs^{-1})		1.67	
7. Time to start-up (months)	56.00	68.00	90.00
8. Levelised cost: capital (£/MWh)	51.30	75.00	79.40
9. Levelised cost: O&M (£/MWh)	10.90	14.30	14.30
10. Levelised cost: fuel (£/MWh)	4.20	5.30	6.30
11. Levelised cost: TOTAL (£/MWh)	66.80	94.60	99.00
12. Fuel price sensitivity (%)	4.44	5.60	6.66
13. Financial incentives (£/MWh)		5.08	

14.1.2 Environmental results

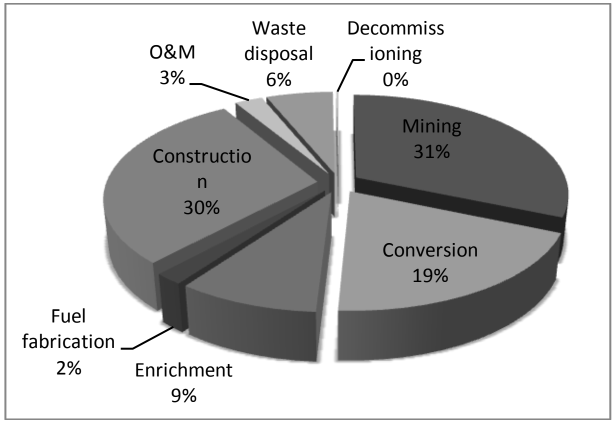
	Nuclear (PWR)			Sensitivity analyses				
	Min.	**Central**	Max.	As central, but 40% of spent fuel reprocessed; 8% MOX use	As central, but plant in USA; enrichment is 30% diffusion, 70% centrifuge [204]	EPR, UCTE, NEEDS, pessimistic scenario [245]	Plant in Switzerland; 40% of spent fuel reprocessed; 8% MOX use [204]	As central, but with end-of-life recycling
14. Recyclability (ratio)	7.33E-01	8.12E-01						
15. Freshwater eco-toxicity (kg DCB eq./kWh)	3.83E-03	2.11E-02	2.58E-02	1.95E-02	2.58E-02	3.83E-03	4.12E-03	2.08E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	6.68E+00	4.02E+01	5.61E+01	3.73E+01	5.61E+01	6.68E+00	7.30E+00	3.95E+01
17. Global warming (kg CO_2 eq./kWh)	5.13E-03	6.24E-03	1.31E-02	6.12E-03	1.31E-02	5.13E-03	5.44E-03	6.11E-03
18. Ozone layer depletion (kg CFC-11 eq./kWh)	5.26E-10	5.41E-10	7.28E-08	5.28E-10	7.28E-08	5.26E-10	5.39E-10	5.38E-10
19. Acidification (kg SO_2 eq./kWh)	3.76E-05	4.40E-05	9.34E-05	4.23E-05	9.34E-05	3.76E-05	4.14E-05	4.32E-05
20. Eutrophication (kg PO_4^{3-} eq./kWh)	6.42E-06	1.32E-05	2.23E-05	1.30E-05	2.23E-05	6.71E-06	6.42E-06	1.19E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	4.50E-06	4.96E-06	8.08E-06	4.73E-06	8.08E-06	4.50E-06	4.72E-06	4.80E-06
22. Land occupation (m^2yr)	5.28E-04	5.49E-04	7.71E-04	5.31E-04	7.71E-04		5.28E-04	5.42E-04
23. Greenfield land use (ratio)		8.75E-01						
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	2.84E-04	7.40E-04	8.77E-04	6.96E-04	8.77E-04	2.84E-04	3.68E-04	7.34E-04


Conversion 0%
Enrichment 1%
Decommissi oning 0%
Mining 9%
Fuel fabrication 0%
Constructio n 7%
O&M 0%
Waste disposal 83%

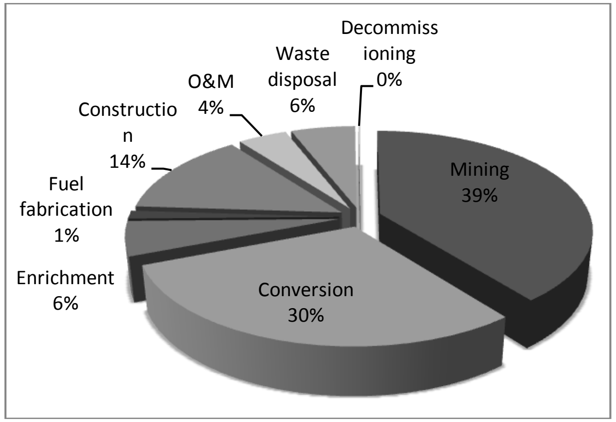
a)


Decommissi oning 0%
Conversion 1%
Mining 10%
Enrichment 1%
Fuel fabrication 0%
Constructio n 7%
O&M 0%
Waste disposal 81%

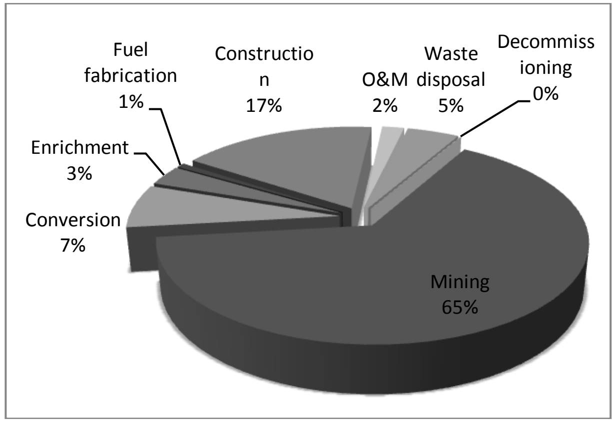
b)


O&M 3%
Waste disposal 6%
Decommiss ioning 0%
Mining 31%
Constructio n 30%
Conversion 19%
Fuel fabrication 2%
Enrichment 9%

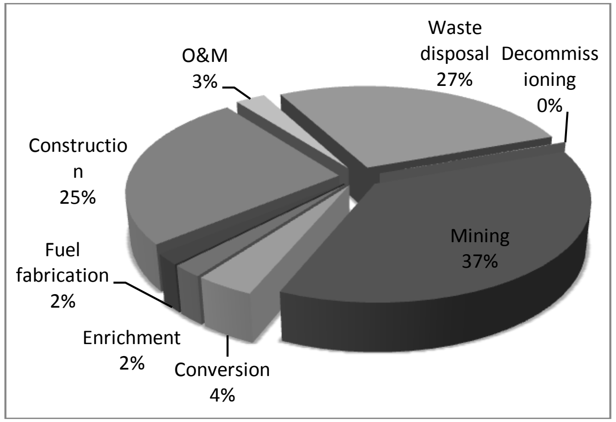
c)


Decommiss ioning 0%
Waste disposal 6%
O&M 4%
Constructio n 14%
Fuel fabrication 1%
Mining 39%
Enrichment 6%
Conversion 30%

d)


Fuel fabrication 1%
Constructio n 17%
O&M 2%
Waste disposal 5%
Decommiss ioning 0%
Enrichment 3%
Conversion 7%
Mining 65%

e)


Waste disposal 27%
Decommiss ioning 0%
O&M 3%
Constructio n 25%
Mining 37%
Fuel fabrication 2%
Enrichment 2%
Conversion 4%

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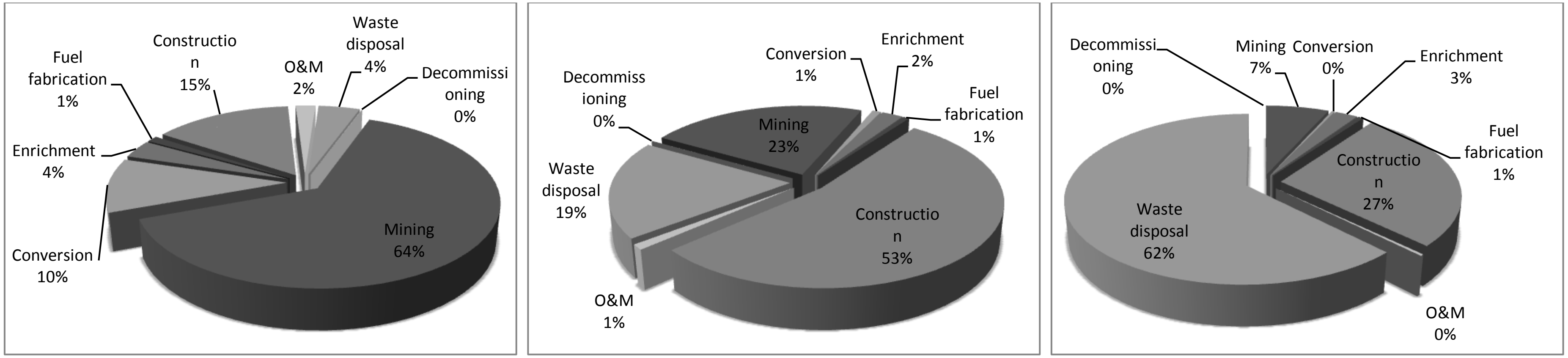


g) **h)** **i)**

Figure 53: Environmental LCA impacts of nuclear power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** freshwater eco-toxicity potential; **b)** marine eco-toxicity potential; **c)** global warming potential; **d)** ozone layer depletion potential; **e)** acidification potential; **f)** eutrophication potential; **g)** photochemical oxidant creation potential; **h)** land occupation; **i)** terrestrial eco-toxicity potential.

14.1.3 Social results

	Nuclear (PWR)			Sensitivity analyses				
	Min.	**Central**	Max.	As central, but 40% of spent fuel reprocessed; 8% MOX use	As central, but plant in USA; enrichment is 30% diffusion, 70% centrifuge [204]	EPR, UCTE, NEEDS, pessimistic scenario [245]	Plant in Switzerland; 40% of spent fuel reprocessed; 8% MOX use [204]	As central, but with end-of-life recycling
25. Direct employment (person-yrs/TWh)		5.59E+01						
26. Total employment (person-yrs/TWh)		8.08E+01						
27. Worker injuries (injuries/TWh)		5.91E-01						
28. Human toxicity potential (kg DCB eq./kWh)	1.35E-02	1.15E-01	1.35E-01	1.06E-01	1.35E-01	1.35E-02	1.59E-02	1.14E-01
29. Health impacts from radiation (DALY/kWh)	2.03E-08	2.03E-08	3.19E-08	2.22E-08	2.34E-08	3.19E-08	2.24E-08	2.03E-08
30. Large accident fatalities (fatalities/PWh)		1.22E-03						
31. Staff hired from local community (%)		n/a						
32. Spending on local suppliers (%)		n/a						
33. Investment in local community (%)		n/a						
34. Human rights and corruption (ordinal scale)		n/a						
35. Fossil fuel avoided (toe/kWh)		2.00E-04						
36. Diversity of fuel supply (dimensionless)		8.40E-01						
37. Fuel storage capabilities (GJ/m^3)		1.04E+07						
38. Nuclear proliferation (ordinal scale)		3.30E+01						
39. Depletion of elements (kg Sb eq./kWh)	4.34E-08	4.74E-08	6.21E-08	4.50E-08	6.21E-08	4.37E-08	5.22E-08	4.34E-08
40. Depletion of fossil fuels (MJ/kWh)	6.62E-02	8.07E-02	1.51E-01	7.86E-02	1.51E-01	6.62E-02	7.07E-02	7.95E-02
41. Volume of radwaste to be stored (m^3/TWh)	9.13E+00	1.02E+01	1.12E+01					
42. Volume of liquid CO2 to be stored (m^3/TWh)		0.00E+00						

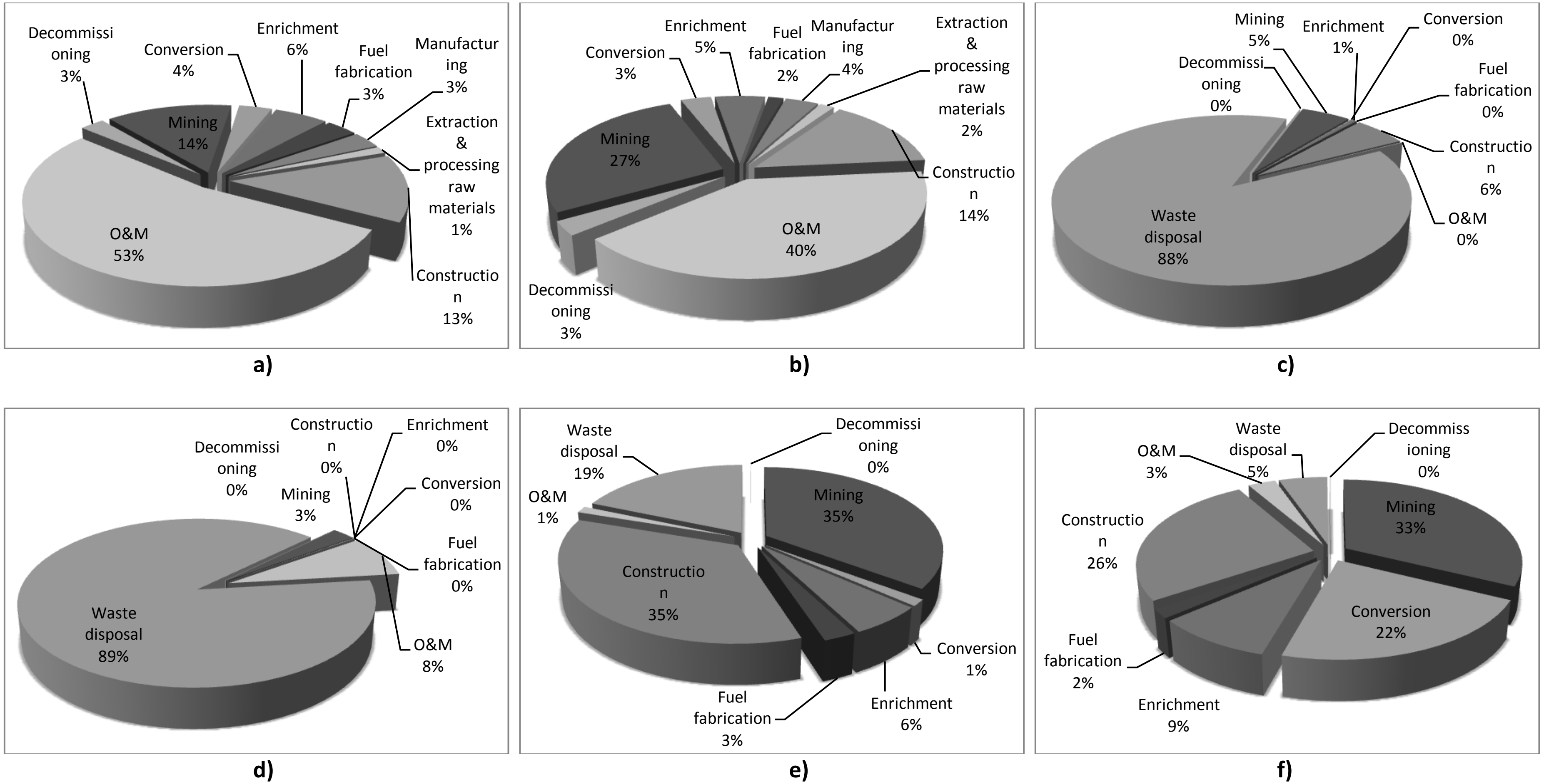


Figure 54: Social impacts of nuclear power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** employment; **b)** worker injuries; **c)** human toxicity potential; **d)** health impacts from radiation; **e)** abiotic depletion (elements); **f)** abiotic depletion (fossil fuels)

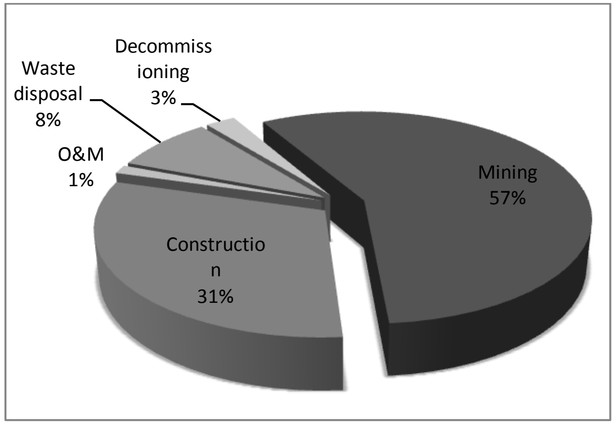
14.2 Natural gas power

14.2.1 Techno-economic results

	Natural gas (CCGT)		
	Min.	**Central**	Max.
1. Capacity factor (%)	53.77	62.15	69.69
2. Availability factor (%)	76.00	88.70	95.00
3. Technical dispatch. (no units)	6.00	7.67	9.00
4. Economic dispatch. (no units)	16.89	17.05	18.87
5. Lifetime of fuel reserves (yrs)	45.00	62.80	250.00
6. Technological lock-in resistance (yrs^{-1})		16.00	
7. Time to start-up (months)	36.00	37.50	42.00
8. Levelised cost: capital (£/MWh)	11.10	11.20	12.40
9. Levelised cost: O&M (£/MWh)	6.00	6.00	6.00
10. Levelised cost: fuel (£/MWh)	25.40	48.50	66.40
11. Levelised cost: TOTAL (£/MWh)	42.50	65.70	83.60
12. Fuel price sensitivity (%)	38.66	73.82	101.07
13. Financial incentives (£/MWh)		0.00	

14.2.2 Environmental results

	Natural gas (CCGT)			Sensitivity analyses		
	Min.	**Central**	Max.	As central, but 100% LNG	As central, but without LNG (100% North Sea gas via pipeline)	As central, but with end-of-life recycling and without LNG (100% North Sea gas via pipeline)
14. Recyclability (ratio)	7.94E-01	8.93E-01				
15. Freshwater eco-toxicity (kg DCB eq./kWh)	1.72E-03	2.57E-03	7.73E-03	7.73E-03	2.00E-03	1.72E-03
16. Marine eco-toxicity (kg DCB eq./kWh)	3.60E+00	7.08E+00	3.07E+01	3.07E+01	4.45E-03	3.60E+00
17. Global warming (kg CO_2 eq./kWh)	3.66E-01	3.79E-01	4.96E-01	4.96E-01	3.66E-01	3.66E-01
18. Ozone layer depletion (kg CFC-11 eq./kWh)	2.80E-09	1.27E-08	1.37E-08	2.80E-09	1.38E-08	1.37E-08
19. Acidification (kg SO_2 eq./kWh)	1.22E-04	1.48E-04	3.70E-04	3.70E-04	1.23E-04	1.22E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	6.00E-05	6.23E-05	7.11E-05	7.11E-05	6.13E-05	6.00E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	2.31E-05	2.73E-05	6.30E-05	6.30E-05	2.33E-05	2.31E-05
22. Land occupation (m^2yr)	2.76E-04	6.33E-04	3.79E-03	3.79E-03	2.82E-04	2.76E-04
23. Greenfield land use (ratio)		0.00E+00				
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	1.16E-04	1.58E-04	5.31E-04	5.31E-04	1.16E-04	1.16E-04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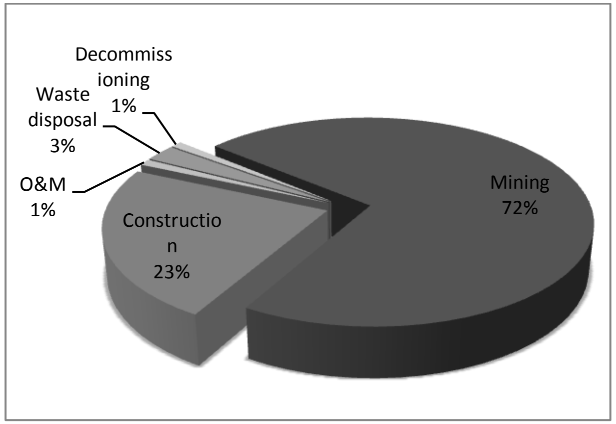
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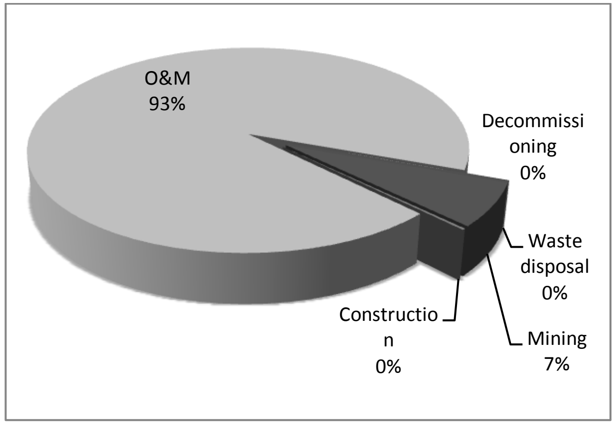
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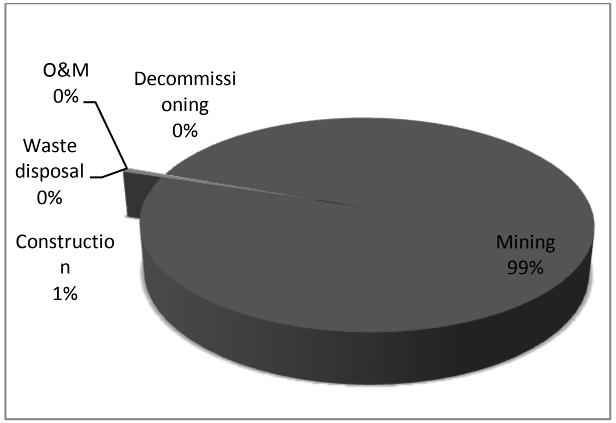
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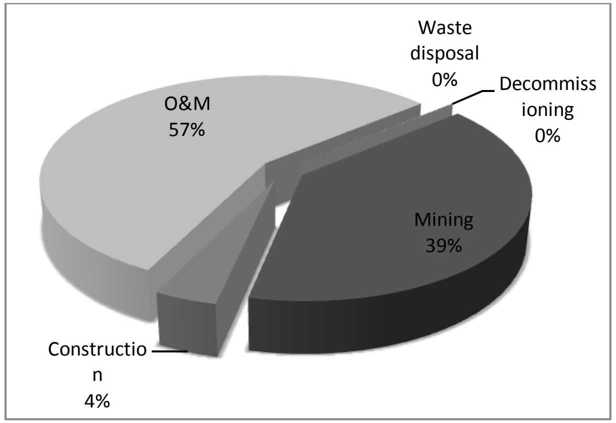
Waste
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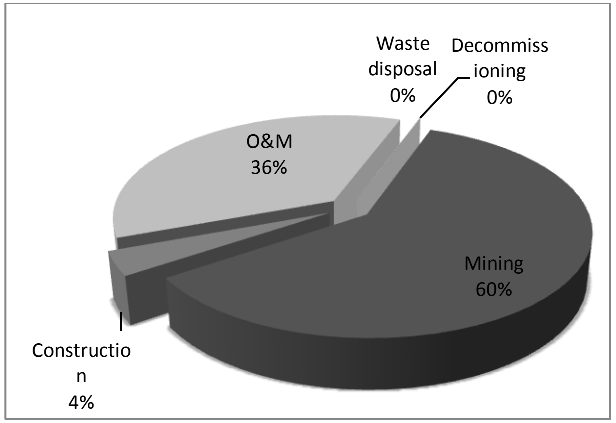
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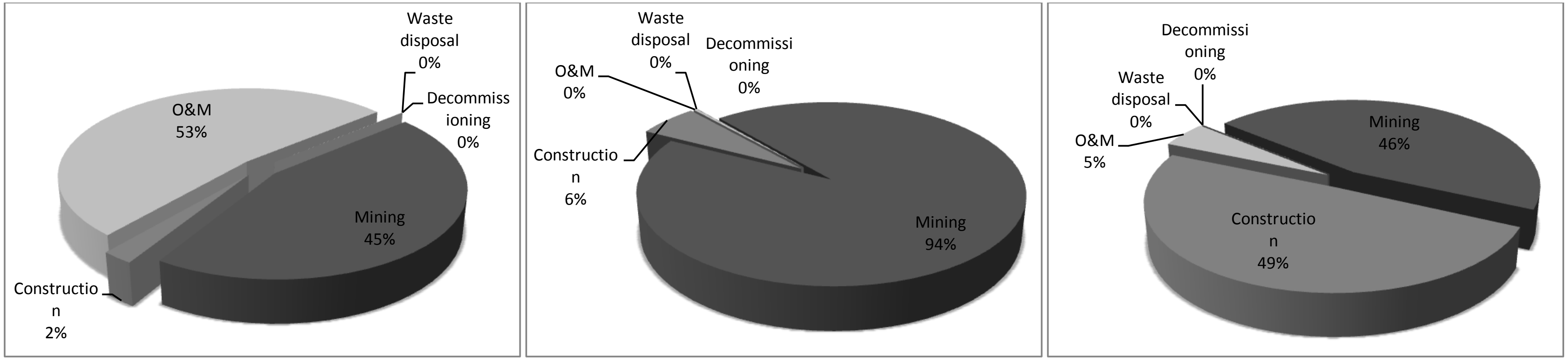


g) **h)** **i)**

Figure 55: Environmental LCA impacts of natural gas power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** freshwater eco-toxicity potential; **b)** marine eco-toxicity potential; **c)** global warming potential; **d)** ozone layer depletion potential; **e)** acidification potential; **f)** eutrophication potential; **g)** photochemical oxidant creation potential; **h)** land occupation; **i)** terrestrial eco-toxicity potential.

14.2.3 Social results

	Natural gas (CCGT)			Sensitivity analyses		
	Min.	**Central**	Max.	As central, but 100% LNG	As central, but without LNG (100% North Sea gas via pipeline)	As central, but with end-of-life recycling and without LNG (100% North Sea gas via pipeline)
25. Direct employment (person-yrs/TWh)		2.66E+01				
26. Total employment (person-yrs/TWh)		6.24E+01				
27. Worker injuries (injuries/TWh)		5.41E-01				
28. Human toxicity potential (kg DCB eq./kWh)	3.68E-03	5.44E-03	1.41E-02	1.41E-02	4.48E-03	3.68E-03
29. Health impacts from radiation (DALY/kWh)	1.16E-11	2.63E-10	2.53E-09	2.53E-09	1.16E-11	1.28E-11
30. Large accident fatalities (fatalities/PWh)		5.08E+00				
31. Staff hired from local community (%)		n/a				
32. Spending on local suppliers (%)		n/a				
33. Investment in local community (%)		n/a				
34. Human rights and corruption (ordinal scale)		n/a				
35. Fossil fuel avoided (toe/kWh)		0.00E+00				
36. Diversity of fuel supply (dimensionless)		8.70E-01				
37. Fuel storage capabilities (GJ/m^3)		3.58E-02				
38. Nuclear proliferation (ordinal scale)		0.00E+00				
39. Depletion of elements (kg Sb eq./kWh)	1.82E-08	2.83E-08	8.06E-08	8.06E-08	2.25E-08	1.82E-08
40. Depletion of fossil fuels (MJ/kWh)	5.66E+00	5.75E+00	6.51E+00	6.51E+00	5.67E+00	5.66E+00
41. Volume of radwaste to be stored (m^3/TWh)		0.00E+00				
42. Volume of liquid CO2 to be stored (m^3/TWh)		0.00E+00				

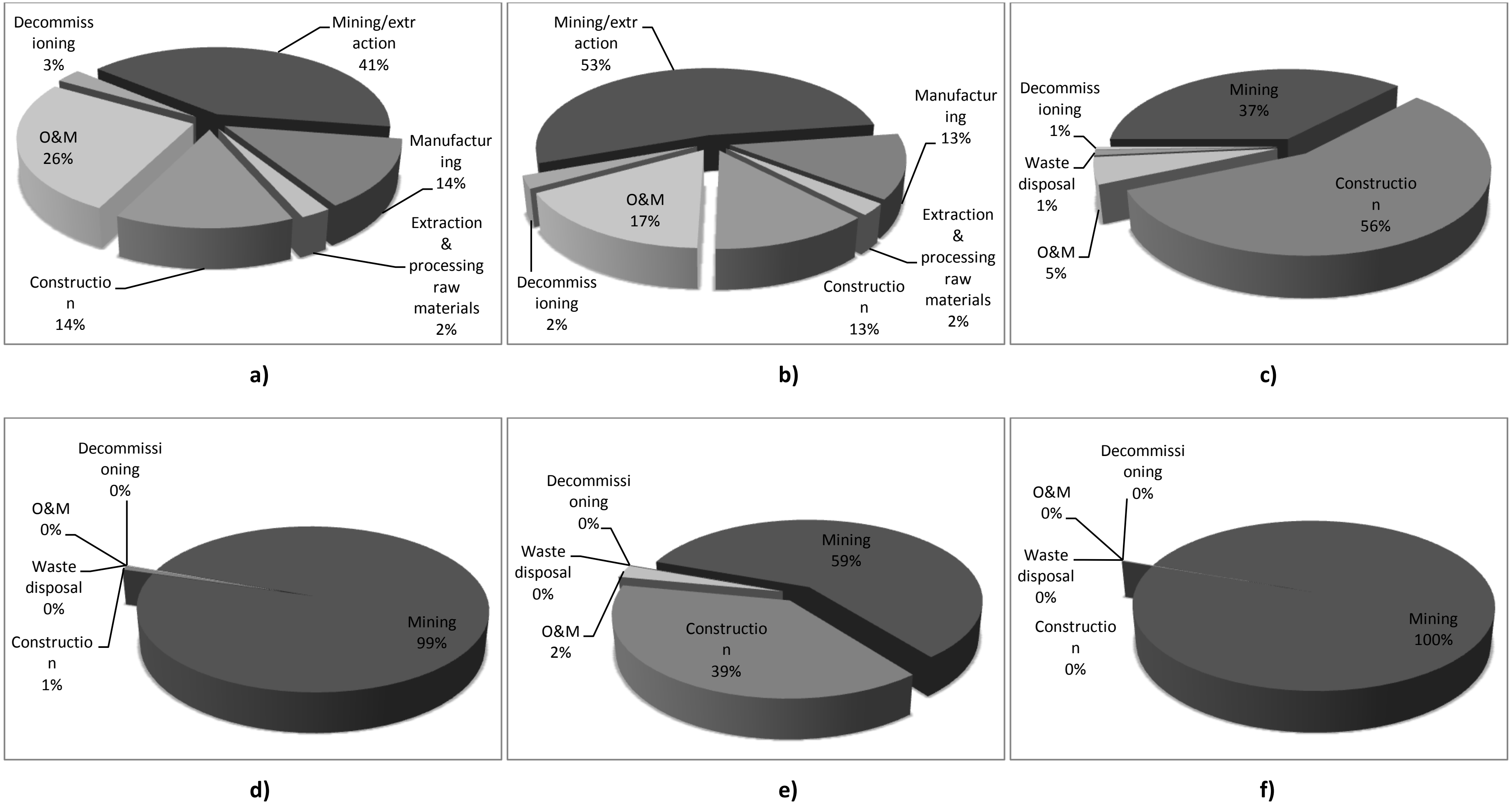


Figure 56: Social impacts of natural gas power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** employment; **b)** worker injuries; **c)** human toxicity potential; **d)** health impacts from radiation; **e)** abiotic depletion (elements); **f)** abiotic depletion (fossil fuels)

14.3 Coal power

14.3.1 Techno-economic results

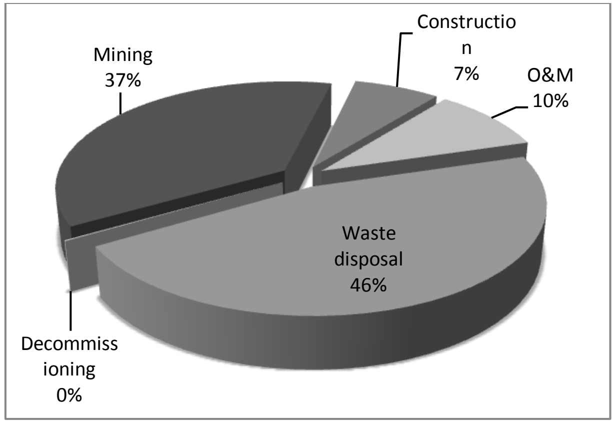
	Coal (pulverised)		
	Min.	**Central**	Max.
1. Capacity factor (%)	49.76	62.32	72.90
2. Availability factor (%)		87.10	90.70
3. Technical dispatch. (no units)	4.00	4.67	6.00
4. Economic dispatch. (no units)	38.20	56.89	82.99
5. Lifetime of fuel reserves (yrs)	61.00	119.00	2184.00
6. Technological lock-in resistance (yrs^{-1})		8.89	
7. Time to start-up (months)	48.00	56.00	72.00
8. Levelised cost: capital (£/MWh)	28.40	42.30	61.70
9. Levelised cost: O&M (£/MWh)	10.70	11.95	13.10
10. Levelised cost: fuel (£/MWh)	13.00	20.10	24.40
11. Levelised cost: TOTAL (£/MWh)	52.60	74.35	95.00
12. Fuel price sensitivity (%)	17.48	27.03	32.82
13. Financial incentives (£/MWh)		0.00	

14.3.2 Environmental results

	Coal (pulverised)			Sensitivity analyses						
	Min.	**Central**	Max.	Ecoinvent hard coal, Germany [204]	Ecoinvent hard coal, USA - ERCOT [204]	Ecoinvent hard coal, USA - FRCC [204]	Ecoinvent hard coal, USA - MRO [204]	Ecoinvent hard coal, USA - NPCC [204]	Ecoinvent hard coal, USA - RFC [204]	Ecoinvent hard coal, USA - SERC [204]
14. Recyclability (ratio)	7.77E-01	8.43E-01	8.43E-01							
15. Freshwater eco-toxicity (kg DCB eq./kWh)	5.27E-03	1.67E-02	9.58E-02	1.23E-02	8.13E-02	6.56E-02	9.58E-02	7.59E-02	7.33E-02	7.54E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	5.66E+02	5.78E+02	1.91E+03	5.66E+02	1.62E+03	1.32E+03	1.91E+03	1.53E+03	1.49E+03	1.52E+03
17. Global warming (kg CO_2 eq./kWh)	9.65E-01	1.07E+00	1.48E+00	1.09E+00	1.25E+00	9.98E-01	1.48E+00	1.14E+00	1.13E+00	1.16E+00
18. Ozone layer depletion (kg CFC-11 eq./kWh)	3.20E-09	4.25E-09	1.05E-08	3.69E-09	9.10E-09	6.20E-09	1.05E-08	7.31E-09	6.97E-09	7.66E-09
19. Acidification (kg SO_2 eq./kWh)	1.66E-03	1.78E-03	9.80E-03	1.66E-03	4.63E-03	5.15E-03	7.29E-03	8.26E-03	9.80E-03	8.20E-03
20. Eutrophication (kg PO_4^{3-} eq./kWh)	1.41E-04	2.15E-04	5.89E-04	1.67E-04	3.01E-04	3.96E-04	5.89E-04	3.24E-04	3.84E-04	3.78E-04
21. Photochemical smog (kg C_2H_4 eq./kWh)	1.33E-04	1.40E-04	4.57E-04	1.33E-04	2.64E-04	2.67E-04	3.99E-04	3.93E-04	4.57E-04	3.99E-04
22. Land occupation (m^2yr)	2.07E-02	2.73E-02	4.04E-02	3.53E-02	3.43E-02	2.07E-02	4.04E-02	2.40E-02	2.33E-02	2.72E-02
23. Greenfield land use (ratio)		1.67E-01								
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	6.13E-04	1.53E-03	1.78E-03	1.48E-03	1.73E-03	9.43E-04	1.78E-03	1.30E-03	1.65E-03	1.45E-03

(continued overleaf)

	Sensitivity analyses (continued)			
	Ecoinvent hard coal, USA - SPP [204]	Ecoinvent hard coal, USA - WECC [204]	Ecoinvent hard coal, NORDEL [204]	As central, but with end-of-life recycling
14. Recyclability (ratio)				
15. Freshwater eco-toxicity (kg DCB eq./kWh)	9.29E-02	8.07E-02	5.27E-03	1.63E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	1.86E+03	1.60E+03	9.88E+02	5.77E+02
17. Global warming (kg CO_2 eq./kWh)	1.42E+00	1.24E+00	9.65E-01	1.07E+00
18. Ozone layer depletion (kg CFC-11 eq./kWh)	9.34E-09	8.88E-09	3.20E-09	4.23E-09
19. Acidification (kg SO_2 eq./kWh)	6.66E-03	4.07E-03	2.14E-03	1.77E-03
20. Eutrophication (kg PO_4^{3-} eq./kWh)	4.99E-04	4.75E-04	1.41E-04	2.12E-04
21. Photochemical smog (kg C_2H_4 eq./kWh)	3.55E-04	2.52E-04	1.43E-04	1.40E-04
22. Land occupation (m^2yr)	3.28E-02	3.40E-02	3.15E-02	2.73E-02
23. Greenfield land use (ratio)				
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	1.57E-03	1.38E-03	6.13E-04	1.54E-03


Mining
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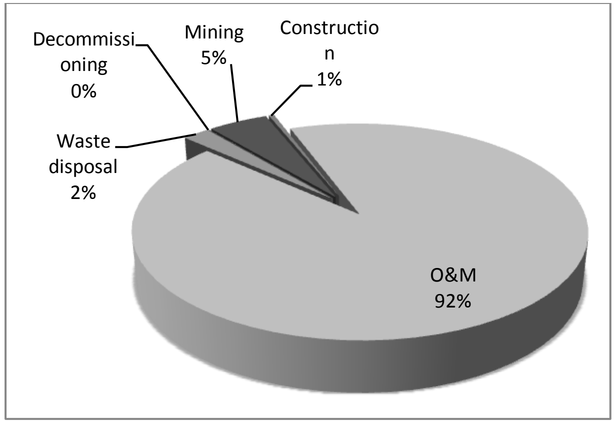
a)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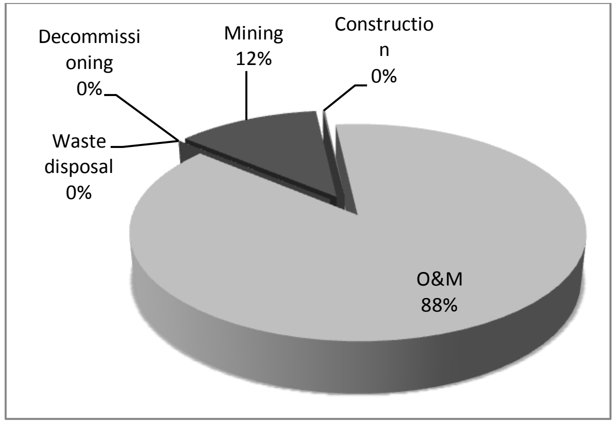
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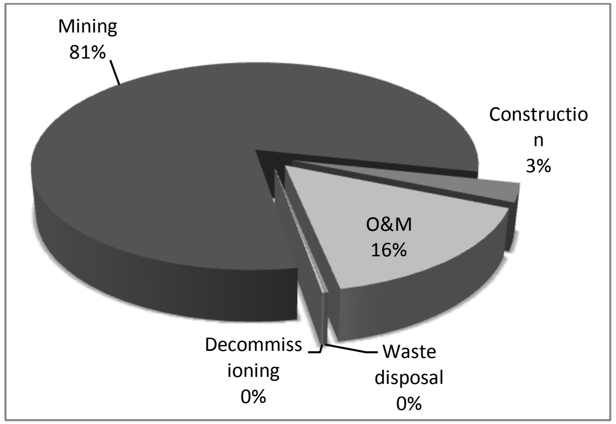
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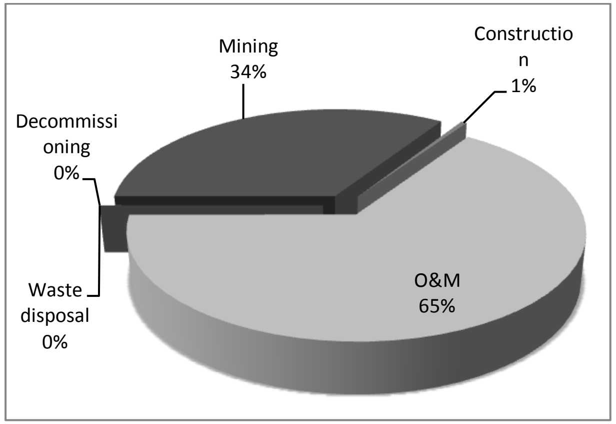
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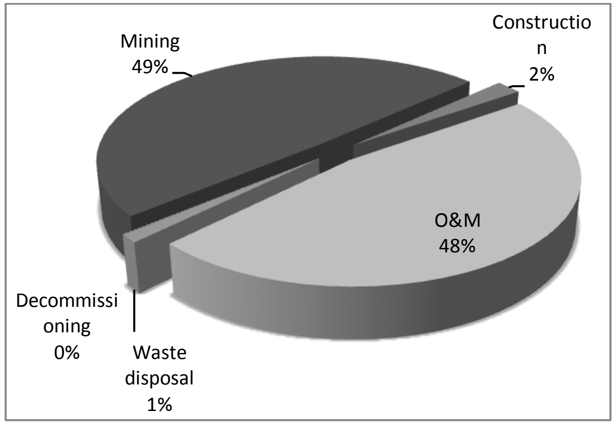
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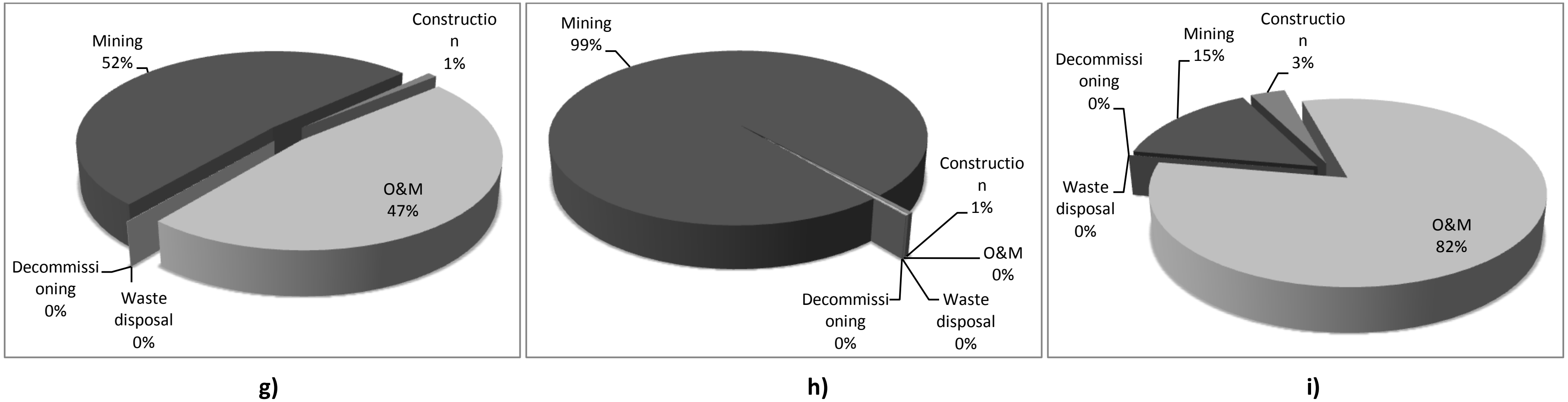


Figure 57: Environmental LCA impacts of coal power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** freshwater eco-toxicity potential; **b)** marine eco-toxicity potential; **c)** global warming potential; **d)** ozone layer depletion potential; **e)** acidification potential; **f)** eutrophication potential; **g)** photochemical oxidant creation potential; **h)** land occupation; **i)** terrestrial eco-toxicity potential.

14.3.3 Social results

	Coal (pulverised)			Sensitivity analyses						
	Min.	**Central**	Max.	Ecoinvent hard coal, Germany [204]	Ecoinvent hard coal, USA - ERCOT [204]	Ecoinvent hard coal, USA - FRCC [204]	Ecoinvent hard coal, USA - MRO [204]	Ecoinvent hard coal, USA - NPCC [204]	Ecoinvent hard coal, USA - RFC [204]	Ecoinvent hard coal, USA - SERC [204]
25. Direct employment (person-yrs/TWh)		5.56E+01								
26. Total employment (person-yrs/TWh)		1.91E+02								
27. Worker injuries (injuries/TWh)		4.50E+00								
28. Human toxicity potential (kg DCB eq./kWh)	7.28E-02	7.77E-02	3.52E-01	7.28E-02	2.97E-01	2.42E-01	3.52E-01	2.79E-01	2.72E-01	2.78E-01
29. Health impacts from radiation (DALY/kWh)	7.10E-10	7.10E-10	2.21E-09	9.45E-10	1.84E-09	1.27E-09	2.21E-09	1.60E-09	1.43E-09	1.56E-09
30. Large accident fatalities (fatalities/PWh)		2.07E+01								
31. Staff hired from local community (%)		n/a								
32. Spending on local suppliers (%)		n/a								
33. Investment in local community (%)		n/a								
34. Human rights and corruption (ordinal scale)		n/a								
35. Fossil fuel avoided (toe/kWh)		0.00E+00								
36. Diversity of fuel supply (dimensionless)		7.20E-01								
37. Fuel storage capabilities (GJ/m^3)		2.12E+01								
38. Nuclear proliferation (ordinal scale)		0.00E+00								
39. Depletion of elements (kg Sb eq./kWh)	8.96E-08	9.72E-08	3.50E-07	1.09E-07	2.97E-07	1.95E-07	3.50E-07	2.35E-07	2.18E-07	2.44E-07
40. Depletion of fossil fuels (MJ/kWh)	1.26E+01	1.51E+01	2.47E+01	1.66E+01	2.10E+01	1.26E+01	2.47E+01	1.46E+01	1.42E+01	1.66E+01
41. Volume of radwaste to be stored (m^3/TWh)		0.00E+00								
42. Volume of liquid CO2 to be stored (m^3/TWh)		0.00E+00								

(continued overleaf)

	Sensitivity analyses (continued)			
	Ecoinvent hard coal, USA - SPP [204]	Ecoinvent hard coal, USA - WECC [204]	Ecoinvent hard coal, NORDEL [204]	As central, but with end-of-life recycling
25. Direct employment (person-yrs/TWh)				
26. Total employment (person-yrs/TWh)				
27. Worker injuries (injuries/TWh)				
28. Human toxicity potential (kg DCB eq./kWh)	3.41E-01	2.96E-01	8.93E-02	7.63E-02
29. Health impacts from radiation (DALY/kWh)	1.94E-09	1.84E-09	8.32E-10	7.12E-10
30. Large accident fatalities (fatalities/PWh)				
31. Staff hired from local community (%)				
32. Spending on local suppliers (%)				
33. Investment in local community (%)				
34. Human rights and corruption (ordinal scale)				
35. Fossil fuel avoided (toe/kWh)				
36. Diversity of fuel supply (dimensionless)				
37. Fuel storage capabilities (GJ/m^3)				
38. Nuclear proliferation (ordinal scale)				
39. Depletion of elements (kg Sb eq./kWh)	3.00E-07	2.94E-07	9.48E-08	8.96E-08
40. Depletion of fossil fuels (MJ/kWh)	2.00E+01	2.08E+01	1.49E+01	1.51E+01
41. Volume of radwaste to be stored (m^3/TWh)				
42. Volume of liquid CO2 to be stored (m^3/TWh)				

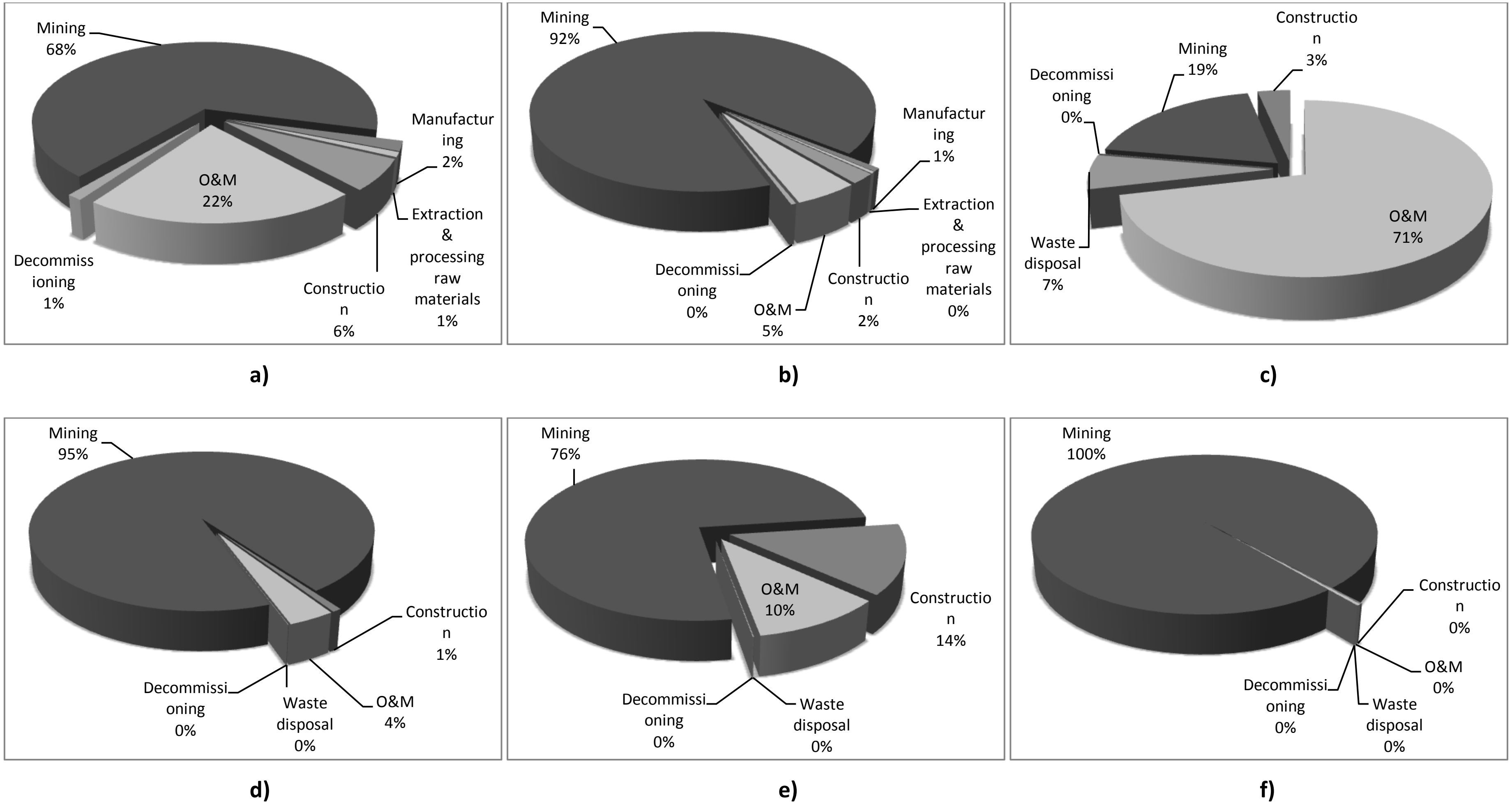


Figure 58: Social impacts of coal power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** employment; **b)** worker injuries; **c)** human toxicity potential; **d)** health impacts from radiation; **e)** abiotic depletion (elements); **f)** abiotic depletion (fossil fuels)

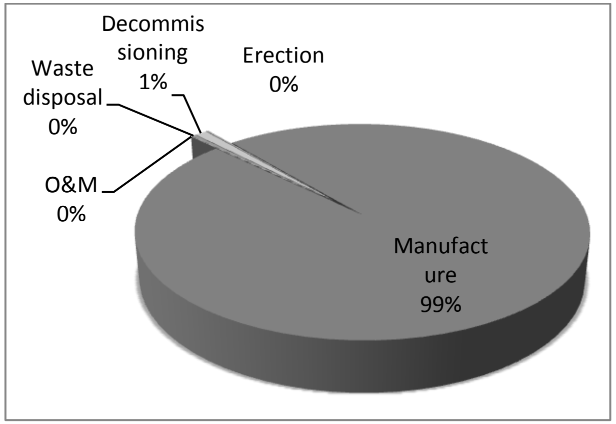
14.4 Offshore wind power

14.4.1 Techno-economic results

	Wind (offshore)		
	Min.	**Central**	Max.
1. Capacity factor (%)	25.60	30.00	40.00
2. Availability factor (%)	67.00	81.40	98.00
3. Technical dispatch. (no units)		16.00	
4. Economic dispatch. (no units)	60.58	74.88	98.97
5. Lifetime of fuel reserves (yrs)		∞	
6. Technological lock-in resistance (yrs^{-1})		0.00	
7. Time to start-up (months)	4.00	12.80	20.00
8. Levelised cost: capital (£/MWh)	88.50	109.40	144.60
9. Levelised cost: O&M (£/MWh)	23.00	36.70	45.80
10. Levelised cost: fuel (£/MWh)		0.00	
11. Levelised cost: TOTAL (£/MWh)	111.50	146.10	190.50
12. Fuel price sensitivity (%)		0.00	
13. Financial incentives (£/MWh)		82.46	

14.4.2 Environmental results

	Wind (offshore)			Sensitivity analyses							
	Min.	**Central [315]**	Max.	Vestas V80 2MW, monopile - capacity factor 30% [315]	Vestas V80 2MW, monopile - capacity factor 50% [315]	Bonus 2MW - capacity factor 30%	Vestas V90 3MW, monopile - capacity factor 40%	Vestas V90 3MW, monopile - capacity factor 50% [315]	5MW, monopile - capacity factor 30% [315]	5MW, monopile - capacity factor 50% [315]	As central, but with end-of-life recycling
14. Recyclability (ratio)	8.03E-01	9.94E-01	9.94E-01								
15. Freshwater eco-toxicity (kg DCB eq./kWh)	8.68E-03	2.14E-02	2.14E-02	2.14E-02	1.29E-02	1.48E-02	1.61E-02	1.29E-02	1.45E-02	8.68E-03	1.10E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	1.83E+01	4.64E+01	4.64E+01	4.06E+01	2.45E+01	2.36E+01	3.48E+01	2.79E+01	3.04E+01	1.83E+01	1.88E+01
17. Global warming (kg CO_2 eq./kWh)	4.73E-03	1.12E-02	1.42E-02	1.42E-02	8.54E-03	1.42E-02	8.40E-03	6.73E-03	7.88E-03	4.73E-03	8.00E-03
18. Ozone layer depletion (kg CFC-11 eq./kWh)	2.55E-10	5.96E-10	8.52E-10	7.69E-10	4.66E-10	8.52E-10	4.47E-10	3.58E-10	4.24E-10	2.55E-10	4.82E-10
19. Acidification (kg SO_2 eq./kWh)	3.35E-05	8.29E-05	8.41E-05	8.41E-05	5.07E-05	6.23E-05	6.22E-05	4.98E-05	5.58E-05	3.35E-05	4.64E-05
20. Eutrophication (kg PO_4^{3-} eq./kWh)	2.05E-05	6.01E-05	6.01E-05	5.10E-05	3.09E-05	3.14E-05	4.50E-05	3.61E-05	3.92E-05	2.35E-05	2.05E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	3.47E-06	8.49E-06	9.81E-06	9.81E-06	5.91E-06	7.88E-06	6.37E-06	5.10E-06	5.79E-06	3.47E-06	4.88E-06
22. Land occupation (m^2yr)	1.56E-04	3.74E-04	4.61E-04	4.61E-04	2.76E-04	3.91E-04	2.81E-04	2.25E-04	2.60E-04	1.56E-04	2.46E-04
23. Greenfield land use (ratio)											
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	6.33E-04	1.43E-03	1.93E-03	1.93E-03	1.16E-03	1.77E-03	1.07E-03	8.61E-04	1.06E-03	6.33E-04	1.03E-03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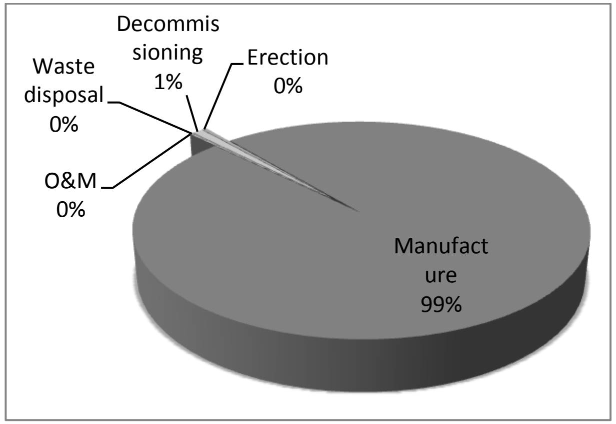
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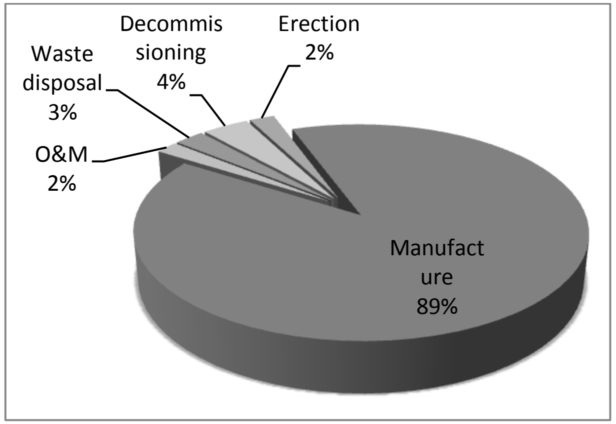
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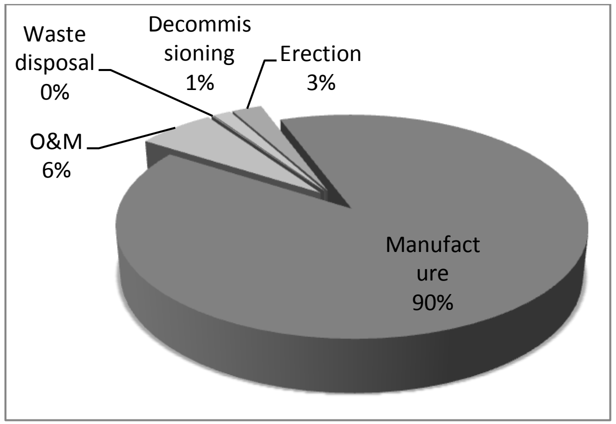
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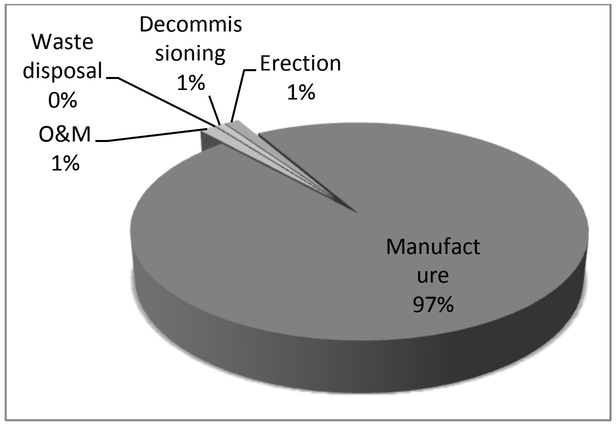
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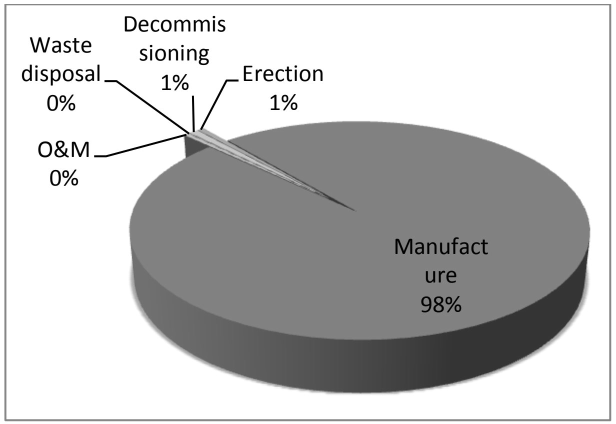
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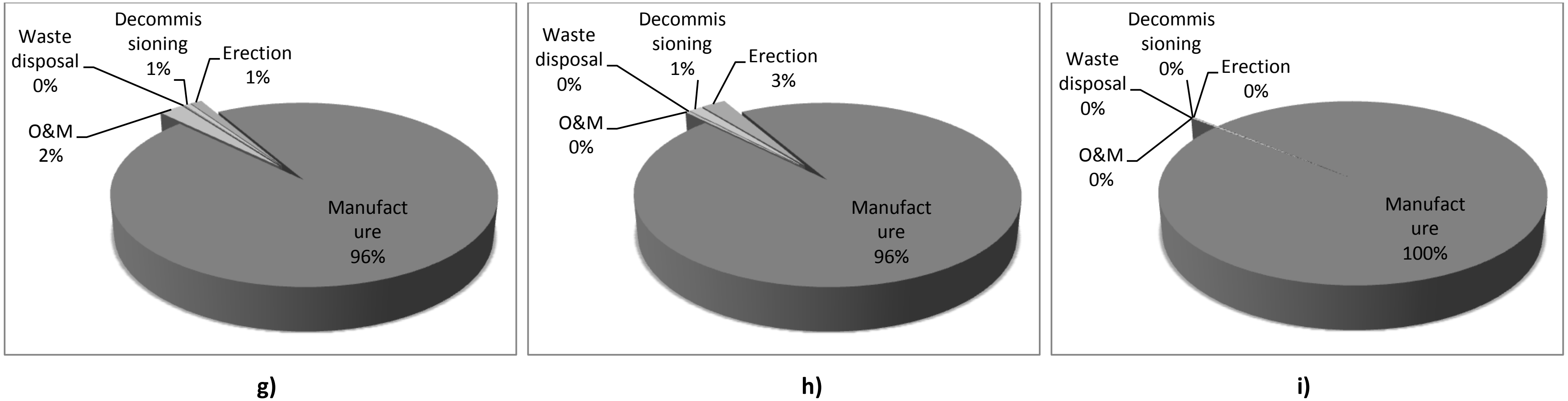


Figure 59: Environmental LCA impacts of offshore wind power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** freshwater eco-toxicity potential; **b)** marine eco-toxicity potential; **c)** global warming potential; **d)** ozone layer depletion potential; **e)** acidification potential; **f)** eutrophication potential; **g)** photochemical oxidant creation potential; **h)** land occupation; **i)** terrestrial eco-toxicity potential

14.4.3 Social results

	Wind (offshore)			Sensitivity analyses							
	Min.	**Central**	Max.	Vestas V80 2MW, monopile - capacity factor 30% [315]	Vestas V80 2MW, monopile - capacity factor 50% [315]	Bonus 2MW - capacity factor 30%	Vestas V90 3MW, monopile - capacity factor 40%	Vestas V90 3MW, monopile - capacity factor 50% [315]	5MW, monopile - capacity factor 30% [315]	5MW, monopile - capacity factor 50% [315]	As central, but with end-of-life recycling
25. Direct employment (person-yrs/TWh)		3.11E+02									
26. Total employment (person-yrs/TWh)		3.68E+02									
27. Worker injuries (injuries/TWh)		2.30E+00									
28. Human toxicity potential (kg DCB eq./kWh)	3.03E-02	7.36E-02	7.52E-02	7.52E-02	4.52E-02	5.89E-02	5.52E-02	4.42E-02	5.05E-02	3.03E-02	3.62E-02
29. Health impacts from radiation (DALY/kWh)	1.86E-11	4.31E-11	6.66E-11	5.47E-11	3.36E-11	4.88E-11	3.23E-11	2.59E-11	3.10E-11	1.86E-11	6.66E-11
30. Large accident fatalities (fatalities/PWh)		7.72E-01									
31. Staff hired from local community (%)		n/a									
32. Spending on local suppliers (%)		n/a									
33. Investment in local community (%)		n/a									
34. Human rights and corruption (ordinal scale)		n/a									
35. Fossil fuel avoided (toe/kWh)		2.00E-04									
36. Diversity of fuel supply (dimensionless)		1.00E+02									
37. Fuel storage capabilities (GJ/m^3)		0.00E+00									
38. Nuclear proliferation (ordinal scale)		0.00E+00									
39. Depletion of elements (kg Sb eq./kWh)	2.96E-07	8.39E-07	8.39E-07	8.24E-07	4.95E-07	2.96E-07	6.29E-07	5.04E-07	5.56E-07	3.34E-07	3.21E-07
40. Depletion of fossil fuels (MJ/kWh)	5.74E-02	1.37E-01	1.74E-01	1.74E-01	1.05E-01	1.59E-01	1.02E-01	8.21E-02	9.57E-02	5.74E-02	1.02E-01
41. Volume of radwaste to be stored (m^3/TWh)		0.00E+00									
42. Volume of liquid CO2 to be stored (m^3/TWh)		0.00E+00									

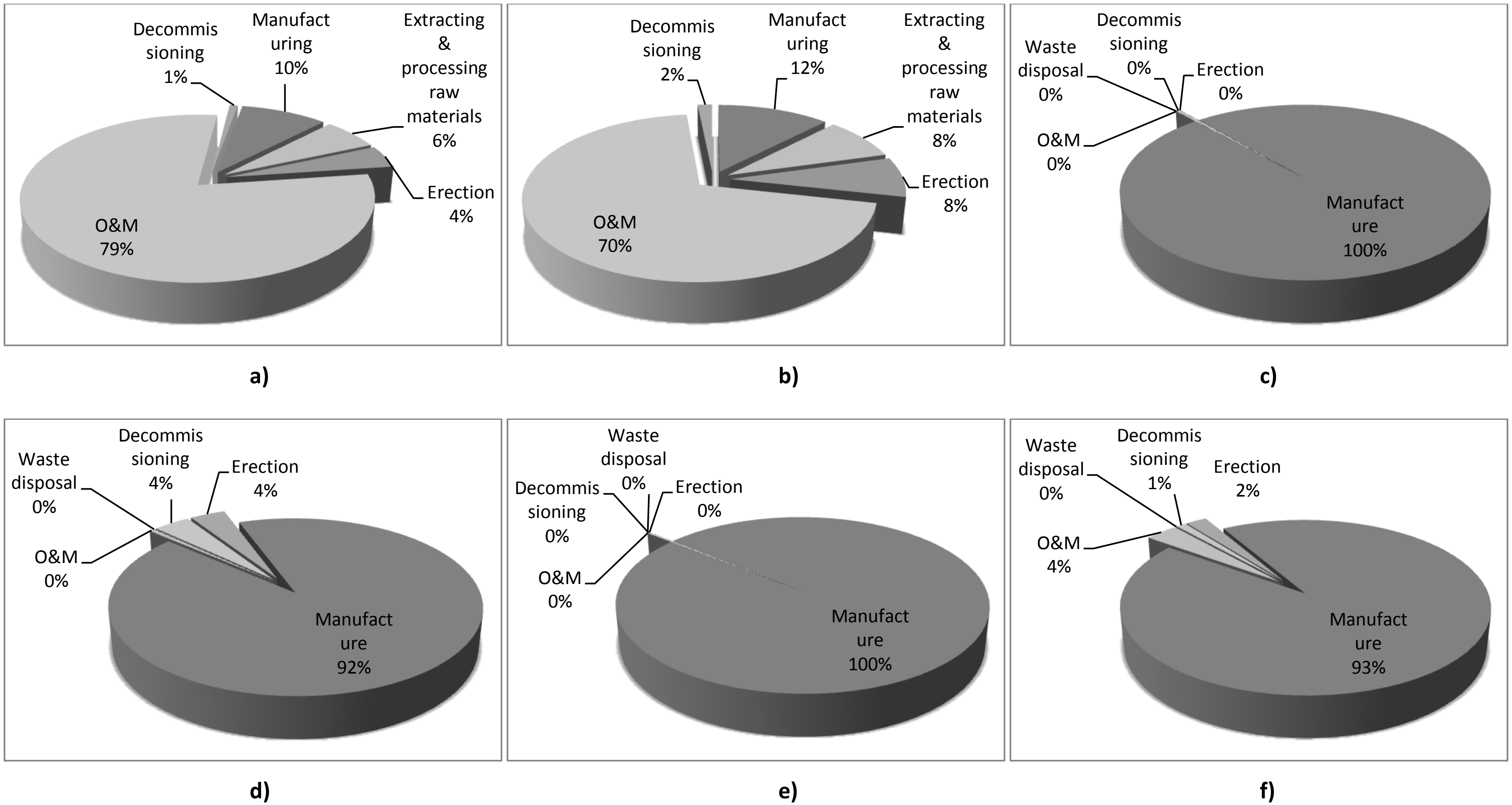


Figure 60: Social impacts of offshore wind power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** employment; **b)** worker injuries; **c)** human toxicity potential; **d)** health impacts from radiation; **e)** abiotic depletion (elements); **f)** abiotic depletion (fossil fuels)

14.5 Solar power

14.5.1 Techno-economic results

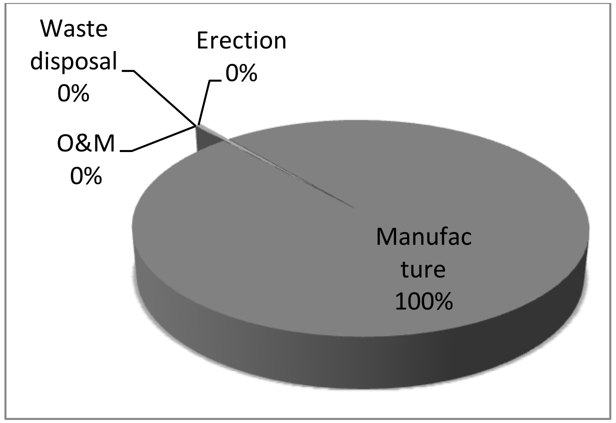
	Solar (PV)		
	Min.	**Central**	Max.
1. Capacity factor (%)	3.99	8.56	10.84
2. Availability factor (%)	90.00	95.90	100.00
3. Technical dispatch. (no units)		16.00	
4. Economic dispatch. (no units)	57.89	93.68	48.85
5. Lifetime of fuel reserves (yrs)		∞	
6. Technological lock-in resistance (yrs^{-1})		0.00	
7. Time to start-up (months)		0.10	9.00
8. Levelised cost: capital (£/MWh)	288.32	466.58	709.86
9. Levelised cost: O&M (£/MWh)	7.76	31.46	89.68
10. Levelised cost: fuel (£/MWh)		0.00	
11. Levelised cost: TOTAL (£/MWh)	296.08	498.04	799.54
12. Fuel price sensitivity (%)		0.00	
13. Financial incentives (£/MWh)		405.50	

14.5.2 Environmental results

	Solar (PV)			Sensitivity analyses						
	Min.	**Central**	Max.	Facade, single-Si, laminate, integrated	Facade, multi-Si, laminate, integrated	Facade, single-Si, panel, mounted	Facade, multi-Si, panel, mounted	Flat roof, single-Si	Flat roof, multi-Si	Slanted roof, single-Si, laminate, integrated
14. Recyclability (ratio)	2.38E-01	9.98E-01	9.98E-01							
15. Freshwater eco-toxicity (kg DCB eq./kWh)	7.32E-03	1.74E-02	2.52E-02	2.24E-02	2.17E-02	2.25E-02	2.18E-02	1.86E-02	1.83E-02	1.42E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	4.04E+01	8.76E+01	1.22E+02	1.22E+02	1.16E+02	1.17E+02	1.11E+02	8.87E+01	8.51E+01	6.95E+01
17. Global warming (kg CO_2 eq./kWh)	6.48E-02	8.78E-02	1.26E-01	1.22E-01	1.09E-01	1.26E-01	1.13E-01	9.14E-02	8.29E-02	7.93E-02
18. Ozone layer depletion (kg CFC-11 eq./kWh)	3.34E-09	1.75E-08	2.52E-08	2.44E-08	2.51E-08	2.45E-08	2.52E-08	1.68E-08	1.72E-08	1.64E-08
19. Acidification (kg SO_2 eq./kWh)	3.16E-04	4.36E-04	6.18E-04	6.14E-04	5.48E-04	6.18E-04	5.53E-04	4.36E-04	3.92E-04	3.93E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	3.81E-05	6.87E-05	1.04E-04	1.03E-04	8.74E-05	1.04E-04	8.85E-05	7.32E-05	6.31E-05	6.71E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	3.39E-05	6.72E-05	9.27E-05	9.18E-05	9.11E-05	9.27E-05	9.21E-05	6.58E-05	6.56E-05	6.00E-05
22. Land occupation (m^2yr)	3.14E-03	4.97E-03	6.82E-03	6.56E-03	6.62E-03	6.76E-03	6.82E-03	4.51E-03	4.55E-03	4.39E-03
23. Greenfield land use (ratio)		0.00E+00								
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	5.60E-04	9.44E-04	1.33E-03	1.23E-03	1.16E-03	1.33E-03	1.27E-03	8.73E-04	8.29E-04	7.81E-04

(continued overleaf)

	Sensitivity analyses (continued)									
	Slanted roof, single-Si, panel, mounted	Slanted roof, multi-Si, laminate, integrated	Slanted roof, multi-Si, panel, mounted	Slanted roof, a-Si, panel, mounted	Slanted roof, a-Si, laminate, integrated	Slanted roof, CdTe, panel, mounted	Slanted roof, CIS, panel, mounted	Slanted roof, ribbon-Si, panel, mounted	Slanted roof, ribbon-Si, laminate, integrated	Slanted roof, single-Si, panel, mounted, **with EOL recycling**
14. Recyclability (ratio)										
15. Freshwater eco-toxicity (kg DCB eq./kWh)	1.52E-02	1.37E-02	1.48E-02	2.52E-02	1.94E-02	1.97E-02	1.42E-02	1.46E-02	1.35E-02	7.32E-03
16. Marine eco-toxicity (kg DCB eq./kWh)	7.96E+01	6.47E+01	7.54E+01	1.16E+02	1.01E+02	9.93E+01	7.44E+01	7.60E+01	6.43E+01	4.04E+01
17. Global warming (kg CO_2 eq./kWh)	8.50E-02	7.01E-02	7.61E-02	8.65E-02	6.86E-02	7.40E-02	7.52E-02	7.14E-02	6.48E-02	7.09E-02
18. Ozone layer depletion (kg CFC-11 eq./kWh)	1.65E-08	1.68E-08	1.70E-08	4.49E-09	3.34E-09	5.63E-09	4.69E-09	1.65E-08	1.63E-08	1.58E-08
19. Acidification (kg SO_2 eq./kWh)	4.17E-04	3.47E-04	3.73E-04	5.04E-04	4.53E-04	5.30E-04	3.40E-04	3.74E-04	3.45E-04	3.16E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	6.98E-05	5.68E-05	5.97E-05	4.56E-05	3.81E-05	5.68E-05	3.91E-05	5.11E-05	4.80E-05	6.05E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	6.25E-05	5.94E-05	6.20E-05	4.71E-05	4.03E-05	4.76E-05	3.39E-05	6.21E-05	5.92E-05	5.28E-05
22. Land occupation (m^2yr)	4.61E-03	4.42E-03	4.66E-03	3.71E-03	3.18E-03	5.84E-03	3.14E-03	4.50E-03	4.24E-03	4.14E-03
23. Greenfield land use (ratio)										
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	8.85E-04	7.31E-04	8.42E-04	1.12E-03	9.28E-04	1.12E-03	7.70E-04	7.95E-04	6.74E-04	5.60E-04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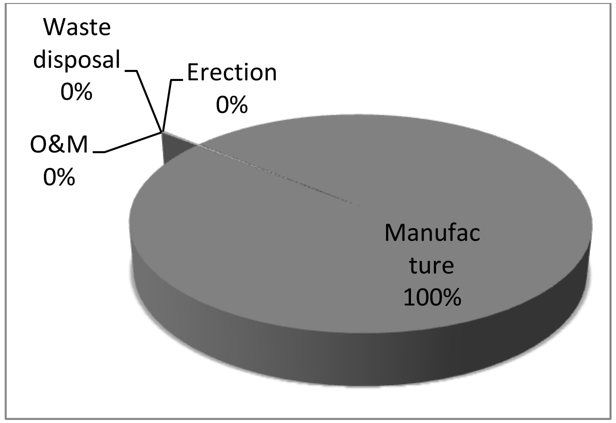
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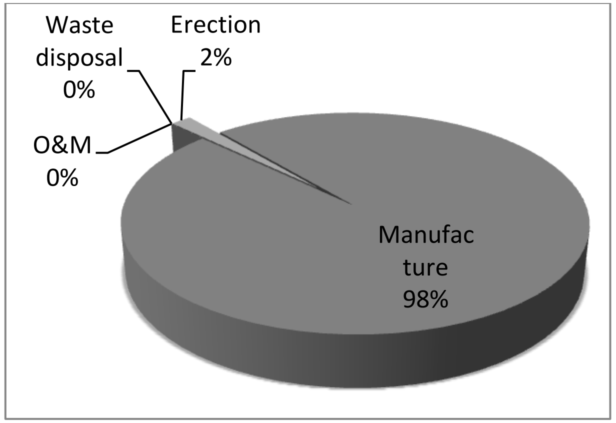
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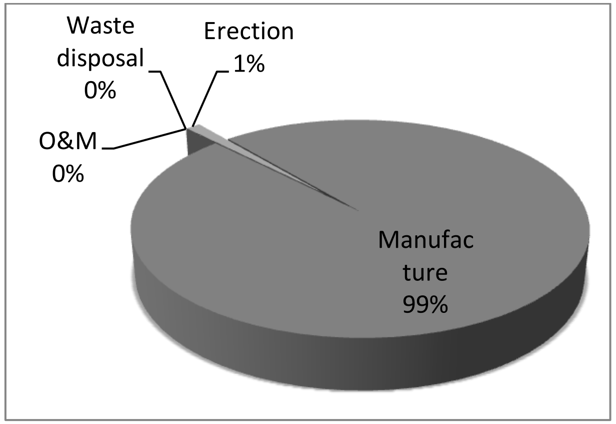
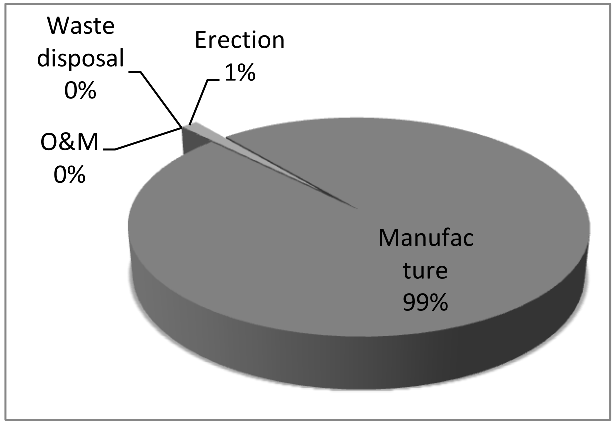
Manufac ture 98%

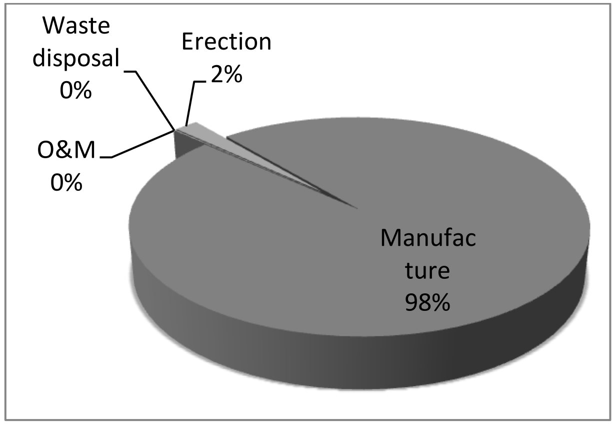
c)


Waste disposal 0%
Erection 1%
O&M 0%
Manufac ture 99%

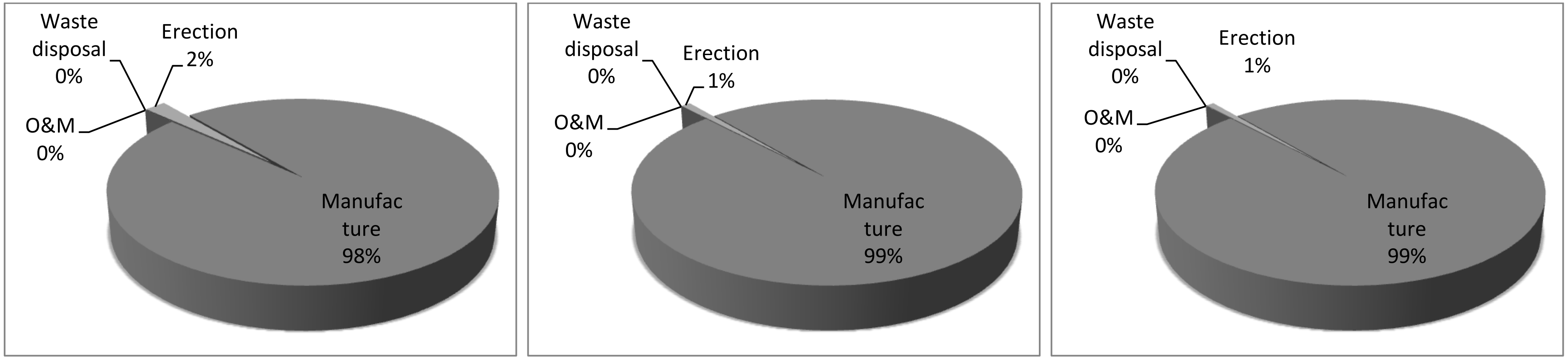
d)


Waste disposal 0%
Erection 1%
O&M 0%
Manufac ture 99%

e)


Waste disposal 0%
Erection 2%
O&M 0%
Manufac ture 98%

f)



g) **h)** **i)**

Figure 61: Environmental LCA impacts of solar photovoltaic power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** freshwater eco-toxicity potential; **b)** marine eco-toxicity potential; **c)** global warming potential; **d)** ozone layer depletion potential; **e)** acidification potential; **f)** eutrophication potential; **g)** photochemical oxidant creation potential; **h)** land occupation; **i)** terrestrial eco-toxicity potential

14.5.3 Social results

	Solar (PV)			Sensitivity analyses						
	Min.	**Central**	Max.	Facade, single-Si, laminate, integrated	Facade, multi-Si, laminate, integrated	Facade, single-Si, panel, mounted	Facade, multi-Si, panel, mounted	Flat roof, single-Si	Flat roof, multi-Si	Slanted roof, single-Si, laminate, integrated
25. Direct employment (person-yrs/TWh)		5.37E+02								
26. Total employment (person-yrs/TWh)		6.53E+02								
27. Worker injuries (injuries/TWh)		4.84E+00								
28. Human toxicity potential (kg DCB eq./kWh)	3.57E-02	8.44E-02	1.15E-01	1.12E-01	1.11E-01	1.15E-01	1.14E-01	7.86E-02	7.79E-02	7.39E-02
29. Health impacts from radiation (DALY/kWh)	1.13E-09	1.99E-09	2.88E-09	2.54E-09	2.43E-09	2.88E-09	2.79E-09	1.80E-09	1.73E-09	1.69E-09
30. Large accident fatalities (fatalities/PWh)		1.14E+00								
31. Staff hired from local community (%)		n/a								
32. Spending on local suppliers (%)		n/a								
33. Investment in local community (%)		n/a								
34. Human rights and corruption (ordinal scale)		n/a								
35. Fossil fuel avoided (toe/kWh)		2.00E-04								
36. Diversity of fuel supply (dimensionless)		1.00E+02								
37. Fuel storage capabilities (GJ/m^3)		0.00E+00								
38. Nuclear proliferation (ordinal scale)		0.00E+00								
39. Depletion of elements (kg Sb eq./kWh)	4.80E-06	1.23E-05	7.51E-05	1.51E-05	1.58E-05	1.53E-05	1.61E-05	1.02E-05	1.07E-05	1.02E-05
40. Depletion of fossil fuels (MJ/kWh)	8.15E-01	1.09E+00	1.58E+00	1.56E+00	1.38E+00	1.58E+00	1.40E+00	1.14E+00	1.02E+00	1.02E+00
41. Volume of radwaste to be stored (m^3/TWh)		0.00E+00								
42. Volume of liquid CO_2 to be stored (m^3/TWh)		0.00E+00								

(continued overleaf)

	Sensitivity analyses (continued)									
	Slanted roof, single-Si, panel, mounted	Slanted roof, multi-Si, laminate, integrated	Slanted roof, multi-Si, panel, mounted	Slanted roof, a-Si, panel, mounted	Slanted roof, a-Si, laminate, integrated	Slanted roof, CdTe, panel, mounted	Slanted roof, CIS, panel, mounted	Slanted roof, ribbon-Si, panel, mounted	Slanted roof, ribbon-Si, laminate, integrated	Slanted roof, single-Si, panel, mounted, **with EOL recycling**
25. Direct employment (person-yrs/TWh)										
26. Total employment (person-yrs/TWh)										
27. Worker injuries (injuries/TWh)										
28. Human toxicity potential (kg DCB eq./kWh)	7.71E-02	7.29E-02	7.63E-02	8.82E-02	7.98E-02	1.06E-01	6.98E-02	7.45E-02	7.07E-02	3.57E-02
29. Health impacts from radiation (DALY/kWh)	1.91E-09	1.62E-09	1.85E-09	1.86E-09	1.39E-09	1.29E-09	1.13E-09	1.47E-09	1.21E-09	1.55E-09
30. Large accident fatalities (fatalities/PWh)										
31. Staff hired from local community (%)										
32. Spending on local suppliers (%)										
33. Investment in local community (%)										
34. Human rights and corruption (ordinal scale)										
35. Fossil fuel avoided (toe/kWh)										
36. Diversity of fuel supply (dimensionless)										
37. Fuel storage capabilities (GJ/m^3)										
38. Nuclear proliferation (ordinal scale)										
39. Depletion of elements (kg Sb eq./kWh)	1.03E-05	1.07E-05	1.08E-05	5.12E-06	4.80E-06	7.51E-05	5.53E-05	1.14E-05	1.13E-05	9.85E-06
40. Depletion of fossil fuels (MJ/kWh)	1.06E+00	8.95E-01	9.44E-01	1.08E+00	9.03E-01	9.54E-01	9.72E-01	8.69E-01	8.15E-01	9.05E-01
41. Volume of radwaste to be stored (m^3/TWh)										
42. Volume of liquid CO2 to be stored (m^3/TWh)										

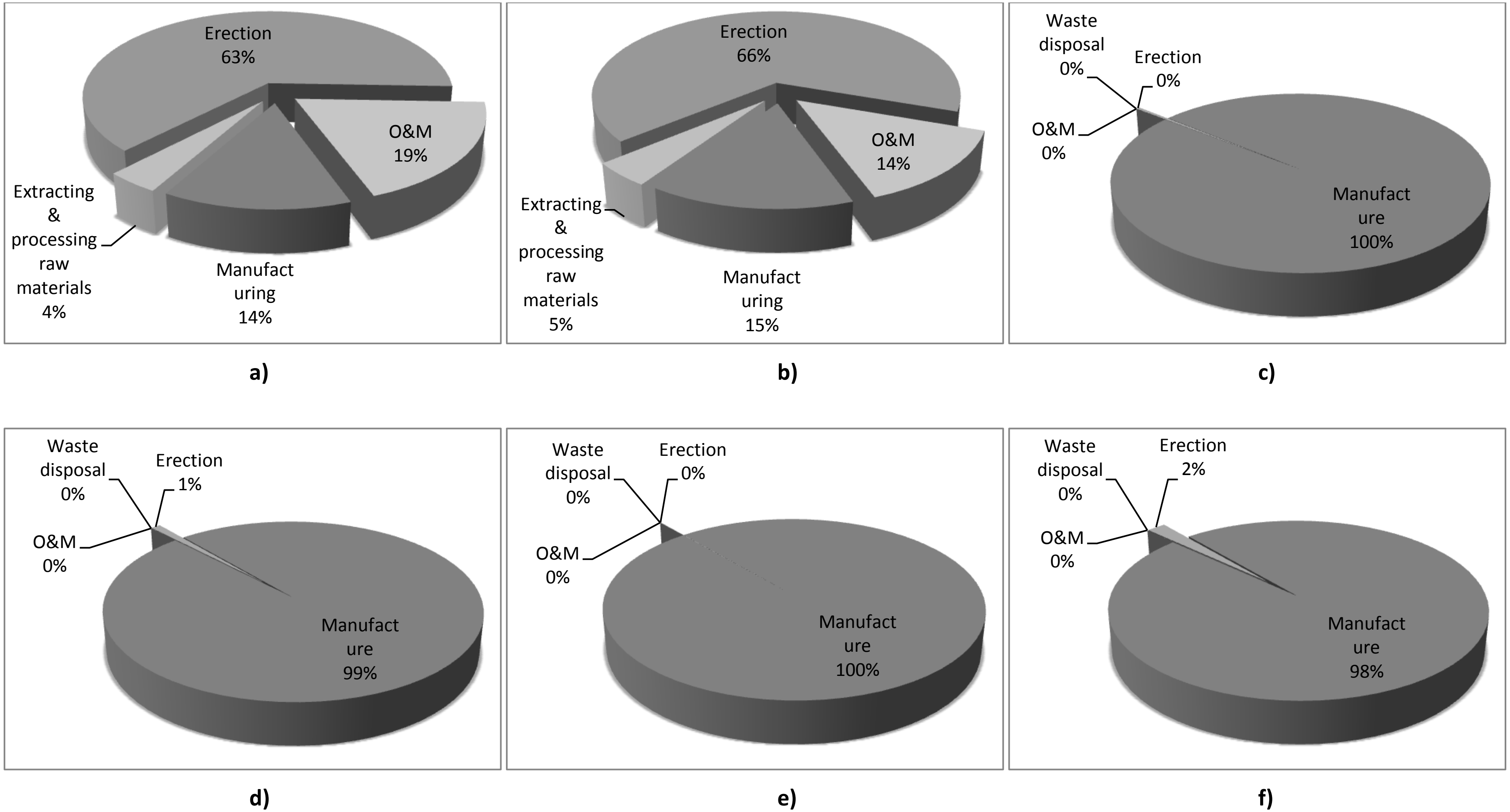


Figure 62: Social impacts of solar photovoltaic power by life cycle stage. *NB/ 'waste disposal' encompasses waste produced at all life cycle stages*. **a)** employment; **b)** worker injuries; **c)** human toxicity potential; **d)** health impacts from radiation; **e)** abiotic depletion (elements); **f)** abiotic depletion (fossil fuels)

15 Appendix 4: Data quality assessment methodology

This appendix describes the process of devising and applying the data quality assessment criteria used in the present study. Firstly, Section 15.1 gives an overview of some previously proposed quality assessment schemes and their relevance to this research, concluding with the assessment criteria chosen for this study. Section 15.2 then gives the method used in this study and the ratings of the results for each technology assessed.

15.1 Data quality assessment criteria proposed by other authors

15.1.1 PAS 2050

PAS 2050 [370] is the UK standard for carbon footprinting. It describes nine criteria for data quality assessment, as follows:

- How specific is the data to the declared **reporting period**? (Ideally the data would cover the exact time period.)
- How specific is it to the product's relevant **geography**?
- How specific is it to the product's relevant **technologies** and processes?
- How **accurate** is the information used (e.g. data, models and assumptions)?
- How **precise** is the information? I.e. measure the variability of the data values.
- How **complete** is it? I.e. is the sample size sufficiently large and representative of all potential sub-categories of the product? What percent of the data used was actually measured vs. taken from a general database?
- How **consistent** is it?
- How **reproducible** is it? I.e. what is the extent to which an independent practitioner could reproduce the results?
- What **sources** are used?

15.1.1.1 Applicability of assessment criteria to the present study

Reporting period: Highly relevant in terms of the age of the data and whether it is appropriate for the purpose of the study.

Geography:	Highly relevant in terms of the correlation of the geographical origin of data with the UK situation. For example, whether fuel mining data corresponds to the UK fuel import mix.
Technologies:	Highly relevant in terms of the correlation of the technology for which data was attained and the technology under assessment.
Accuracy:	Highly relevant
Precision:	Relevant in terms of whether other data have been considered, for example in sensitivity analysis.
Completeness:	Relevant in terms of the number of life cycle stages for which data were available and, for example, the proportion of materials considered during calculation of recyclability or employment.
Consistency:	Relevant in the same sense as the precision criterion.
Reproducibility:	Relevant, although given the referenced data and methodology, the results are inherently reproducible. Validation is a related, relevant issue.
Data sources:	Highly relevant

15.1.2 CCaLC data quality assessment

CCaLC [257] is a carbon footprinting programme developed at the University of Manchester and designed to assist in the reduction of life cycle carbon emissions in different industrial sectors. Data quality assessment in CCaLC involves five criteria (which are themselves based on criteria given in PAS 2050 [370]), each of them assigned a score of 3, 2 or 1 corresponding to ‘high’, ‘medium’, and ‘low’. This scheme is shown in Figure 63.

In a second stage (not shown here), each criterion is weighted according to its perceived importance. This weighting is then multiplied with the score for each criterion. The criteria are weighed such that their weights sum to 10, meaning the maximum possible score for a data point against all five criteria is 30. This overall score is bracketed such that 1-10 is ‘low quality’, 11-20 ‘medium’ and 21-30 ‘high’.

Data quality criteria	Data quality indicators		
	High	Medium	Low
Age of data	< 5 years	5 - 10 years	> 10
Geographical origin of data	Specific	Partly specific	Generic/average
Source of data	Measured and/or modelled based on specific data (e.g. the company data or from suppliers)	Modelled using generic data from LCA databases; some data derived using expert knowledge	Mainly sourced from literature and/or estimated and/or derived using expert knowledge
Completeness of data	All inputs and outputs considered	Majority of relevant inputs and outputs considered	Some relevant inputs and outputs considered or known
Reproducibility /reliability/ consistency of data	Completely reproducible/reliable/ consistent	Partly reproducible/reliable/ consistent	Not reproducible/ not known

Figure 63: Data quality assessment method used in CCaLC [257]

15.1.2.1 Applicability of assessment criteria to the present study

Age of data: Highly relevant

Geographical origin: Highly relevant in terms of the correlation of the geographical origin of data with the UK situation. For example, whether fuel mining data corresponds to the UK fuel import mix.

Source of data: Highly relevant

Completeness: Relevant in terms of the number of life cycle stages for which data were available and, for example, the proportion of materials considered during calculation of recyclability or employment.

Reproducibility: Relevant, although given the referenced data and methodology, the results are inherently reproducible. Validation is a related, relevant issue.

15.1.3 Quintessa Tesla decision support software: evidence support logic

Tesla, by Quintessa [258], is a decision-support programme for use with multi-criteria problems. The documentation for Tesla proposes the following scheme, itself based on Bowden, 2004 [371]:

Quality Indicators

Quality Score	Theoretical basis	Scientific method	Auditability	Calibration	Validation	Objectivity
Vhigh (1)	Well established theory	Best available practice; large sample; direct measure	Well documented trace to data	An exact fit to data	Independent measurement of same variable	No discernible bias
High	Accepted theory; high consensus	Accepted reliable method; small sample; direct measure	Poorly documented but traceable to data	Good fit to data	Independent measurement of high correlation variable	Weak bias
Mod	Accepted theory; low consensus	Accepted method; derived data; analogue; limited reliability	Traceable to data with difficulty	Moderately well correlated with data	Validation measure no truly independent	Moderate bias
Low	Preliminary theory	Preliminary method; unknown reliability	Weak, obscure link to data	Weak correlation to data	Weak, indirect validation	Strong bias
Vlow (0)	Crude speculation	No discernible rigour	No link back to data	No apparent correlation with data	No validation presented	Obvious bias

Figure 64: Data quality assessment method suggested by Quintessa in Tesla [258]

15.1.3.1 Applicability of assessment criteria to the present study

Theoretical basis: Not applicable. None of our evidence is theoretical. The theoretical basis of sustainability assessment or MCDA itself could be questioned, but in that case the value is the same for all data points making this criterion meaningless.

Scientific method: Partly applicable, in that sample size is relevant for some measurements in terms of number of data sources.

Auditability: Highly relevant for all indicators.

Calibration: Not applicable since no computer models have been used to describe observed data.

Validation: Relevant, although difficult to assess where results have not been independently measured but are based on secondary data that have independent analogues. Also not measurable for novel indicators.

Objectivity: Relevant in terms of data source, in that some results may be, at least in part, based on expert judgment.

15.2 Data quality assessment in this study

Drawing on the methods above, the following data quality assessment scheme was developed for use in this study (Table 48):

Table 48: Data quality assessment criteria used in this study

		Criteria						
		Time specificity	**Geographical specificity**	**Technological specificity**	**Completeness of data**	**Data source**	**Auditability**	**Validation**
Score	3 (high)	<5 years old; valid for new build	Matches general UK conditions throughout life cycle	Data for the exact technology under question	All significant inputs and outputs considered; whole life cycle considered	Primary or reputable secondary (e.g. data from company or peer-reviewed)	All data sources documented	Validation possible; result broadly agrees with others
	2 (medium)	5-15 years old; valid only for current capacity	Partly matches UK conditions throughout life cycle	Data for technology very similar to that under question	Majority of inputs and outputs considered; most of life cycle considered	Mainly secondary; some estimation based on expert judgment	Partly documented	Validation possible; Result disagrees with others OR validation partially possible; result agrees
	1 (low)	>15 years old	Geographically generic	More generic data	Missing potentially significant inputs, outputs or life cycle stages	Estimated based on expert judgment	No link to original data	Validation impossible

The result of each indicator for each technology was assessed using the above criteria and scoring system. Following scoring, the output was adapted into a form suitable for implementation in Quintessa Tesla decision-support software in collaboration with National Nuclear Laboratory (NNL). Tesla's Evidence Support Logic module allows users to specify each data point with values from 0 to 1 for three criteria: 'evidence for', 'evidence quality' and 'knowledge base'. The values for the three criteria are then multiplied together to produce an overall score for each data point. In order to fit this format, the values of the criteria shown in Table 48 were grouped and normalised to one, as follows (and as shown in Table 49 to Table 53):

- Evidence for = time specificity + geographical specificity + technological specificity
- Evidence quality = data source + auditability + validation

- Knowledge base = completeness of data

Additionally, Tesla allows users to dictate a level of ‘dependency’ for any indicators within a group. This describes the extent to which the indicators within the group rely on the same data source or influence each other. For instance, in the methodology developed in this study, most of the environmental indicators are derived from LCA. Results for any one LCA model are calculated within LCA software using the life cycle inventory of that model: common values, such as the material and energy requirements of a particular life cycle stage, are used to calculate the results. This commonality means that all the indicator results derived from LCA share a significant level of dependence. Similarly, the worker injuries indicator is based in part on the results of the employment indicator (see Section 3.2.3.2), meaning it is significantly dependent on that result. Like the other three criteria, dependency is rates on a scale from 0 to 1, corresponding to no dependency and total dependency, respectively.

A hierarchical tree was plotted in Tesla depicting the indicators, as in Table 2, and the data quality scores were applied to it to produce the plots shown at the ends of Chapters 4-8 (Figure 9, Figure 15, Figure 21, Figure 26 and Figure 31). The data quality scores for each technology as they were applied in Tesla are shown below in Table 49 to Table 53.

The data quality sections at the ends of Chapters 4-8 give an overview of the reliability of the results for each technology. The total data quality score for the five technologies assessed was typically about 60-70%% (nuclear: 66%, natural gas: 68%, coal: 67%, offshore wind: 69%, solar PV: 69%), with more variance between indicator groups: the techno-economic, environmental and social groups individual ratings varied from 53% (nuclear, environmental) to 76% (natural gas and solar PV, social). Any similarity in data quality scores between technologies was due to shared data sources. For instance, employment estimates for every technology share some of the same underlying data on the mining and processing of metal ores. Similarly, cost data for nuclear, gas, coal and offshore wind rely heavily on one study by Mott MacDonald [201].

Table 49: Data quality scores for the nuclear power assessment

Category	Issue addressed	Indicator	'Evidence for': Time specificity	Geographical specificity	Technological specificity	Normalised total	'Knowledge base': Completeness of data	Normalised total	'Evidence quality': Data source	Auditability	Validation	Normalised total
Techno-economic	Operability	Capacity factor	3	3	2	0.89	3	1.00	3	3	3	1.00
		Availability factor	3	3	2	0.89	3	1.00	2	3	3	0.89
		Technical dispatchability	3	3	2	0.89	3	1.00	1	3	1	0.56
		Economic dispatchability	3	2	3	0.89	3	1.00	3	3	3	1.00
		Lifetime of global fuel reserves at current extraction rates	3	1	2	0.67	3	1.00	3	3	3	1.00
	Technological Lock-in	Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/thermochemical H_2 production) and operational lifetime	3	3	3	1.00	3	1.00	1	2	1	0.44
	Immediacy	Time to plant start-up from start of construction	2	1	1	0.44	2	0.67	3	3	2	0.89
	Levelised Cost of Generation	Capital costs	3	2	3	0.89	3	1.00	3	3	3	1.00
		Operation and maintenance costs	3	2	3	0.89	3	1.00	3	3	3	1.00
		Fuel costs	3	2	3	0.89	3	1.00	3	3	3	1.00
		Decommissioning costs	3	2	3	0.89	2	0.67	3	3	3	1.00
		Total levelised cost	3	2	3	0.89	3	1.00	3	3	3	1.00
	Cost Variability	Fuel price sensitivity	3	2	3	0.89	3	1.00	3	3	3	1.00
	Financial Incentives	Financial incentives and assistance	2	3	1	0.67	1	0.33	3	3	1	0.78

Environmental	**Material Recyclability**	Recyclability of input materials	*1*	*2*	*2*	**0.56**	*2*	**0.67**	*2*	*2*	*3*	**0.78**
	Water Eco-toxicity	Freshwater eco-toxicity potential	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
		Marine eco-toxicity potential	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Global Warming	Global warming potential	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Ozone Layer Depletion	Ozone depletion potential	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Acidification	Acidification potential	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Eutrophication	Eutrophication potential	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Photochemical Smog	Photochemical smog creation potential	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Land Use & Quality	Land occupation	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
		Greenfield land use	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*3*	*1*	**0.67**
		Terrestrial eco-toxicity potential	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
Social	**Provision of Employment**	Direct employment	*3*	*3*	*3*	**1.00**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
		Total employment	*3*	*3*	*3*	**1.00**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
	Human Health Impacts	Worker injuries	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*3*	*3*	*1*	**0.78**
		Human toxicity potential (excluding radiation)	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
		Human health impacts from radiation	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Large Accident Risk	Fatalities due to large accidents	*3*	*1*	*3*	**0.78**	*3*	**1.00**	*2*	*1*	*1*	**0.44**
	Local Community Impacts	Proportion of staff hired from local community relative to total direct employment				**0.00**		**0.00**				**0.00**
		Spending on local suppliers relative to total annual spending				**0.00**		**0.00**				**0.00**
		Direct investment in local community as proportion of total annual profits				**0.00**		**0.00**				**0.00**

Human Rights and Corruption	Involvement of countries in the life cycle with known corruption problems				**0.00**		**0.00**				**0.00**
Energy Security	Amount of imported fossil fuel potentially avoided	*2*	*3*	*2*	**0.78**	*1*	**0.33**	*2*	*3*	*1*	**0.67**
	Diversity of fuel supply mix	*2*	*2*	*1*	**0.56**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Fuel storage capabilities (energy density)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*3*	*1*	**0.67**
Nuclear Proliferation	Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Intergenerational Equity	Use of abiotic resources (elements)	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Use of abiotic resources (fossil fuels)	*1*	*2*	*2*	**0.56**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Volume of radioactive waste to be stored	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Volume of liquid CO_2 to be stored	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*3*	**0.89**

Table 50: Data quality scores for the natural gas power assessment

Category	Issue addressed	Indicator	'Evidence for': Time specificity	Geographical specificity	Technological specificity	Normalised total	'Knowledge base': Completeness of data	Normalised total	'Evidence quality': Data source	Auditability	Validation	Normalised total
Techno-economic	Operability	Capacity factor	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*2*	*3*	*3*	**0.89**
		Availability factor	*3*	*3*	*2*	**0.89**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
		Technical dispatchability	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*1*	*3*	*1*	**0.56**
		Economic dispatchability	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Lifetime of global fuel reserves at current extraction rates	*3*	*1*	*1*	**0.56**	*3*	**1.00**	*3*	*3*	*2*	**0.89**
	Technological Lock-in	Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/thermochemical H_2 production) and operational lifetime	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*1*	*2*	*1*	**0.44**
	Immediacy	Time to plant start-up from start of construction	*3*	*3*	*3*	**1.00**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
	Levelised Cost of Generation	Capital costs	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Operation and maintenance costs	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Fuel costs	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Decommissioning costs	*3*	*2*	*3*	**0.89**	*2*	**0.67**	*3*	*3*	*3*	**1.00**
		Total levelised cost	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
	Cost Variability	Fuel price sensitivity	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
	Financial	Financial incentives and assistance	*2*	*3*	*1*	**0.67**	*1*	**0.33**	*3*	*3*	*1*	**0.78**

	Incentives											
Environmental	**Material Recyclability**	Recyclability of input materials	*3*	*3*	*3*	**1.00**	*2*	**0.67**	*2*	*2*	*3*	**0.78**
	Water Eco-toxicity	Freshwater eco-toxicity potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Marine eco-toxicity potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Global Warming	Global warming potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Ozone Layer Depletion	Ozone depletion potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Acidification	Acidification potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Eutrophication	Eutrophication potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Photochemical Smog	Photochemical smog creation potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Land Use & Quality	Land occupation	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Greenfield land use	*3*	*3*	*3*	**1.00**	*2*	**0.67**	*2*	*1*	*1*	**0.44**
		Terrestrial eco-toxicity potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
Social	**Provision of Employment**	Direct employment	*3*	*2*	*2*	**0.78**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
		Total employment	*3*	*2*	*2*	**0.78**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
	Human Health Impacts	Worker injuries	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*3*	*3*	*1*	**0.78**
		Human toxicity potential (excluding radiation)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Human health impacts from radiation	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Large Accident Risk	Fatalities due to large accidents	*3*	*1*	*1*	**0.56**	*3*	**1.00**	*2*	*1*	*1*	**0.44**
	Local Community Impacts	Proportion of staff hired from local community relative to total direct employment				**0.00**		**0.00**				**0.00**
		Spending on local suppliers relative to total annual spending				**0.00**		**0.00**				**0.00**

	Direct investment in local community as proportion of total annual profits				**0.00**		**0.00**				**0.00**
Human Rights and Corruption	Involvement of countries in the life cycle with known corruption problems				**0.00**		**0.00**				**0.00**
Energy Security	Amount of imported fossil fuel potentially avoided	*2*	*3*	*2*	**0.78**	*1*	**0.33**	*2*	*3*	*1*	**0.67**
	Diversity of fuel supply mix	*2*	*2*	*1*	**0.56**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Fuel storage capabilities (energy density)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Nuclear Proliferation	Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Intergenerational Equity	Use of abiotic resources (elements)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Use of abiotic resources (fossil fuels)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Volume of radioactive waste to be stored	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Volume of liquid CO_2 to be stored	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*3*	**0.89**

Table 51: Data quality scores for the coal power assessment

Category	Issue addressed	Indicator	'Evidence for'				'Knowledge base'		'Evidence quality'			
			Time specificity	*Geographical specificity*	*Technological specificity*	**Normalised total**	*Completeness of data*	**Normalised total**	*Data source*	*Auditability*	*Validation*	**Normalised total**
Techno-economic	Operability	Capacity factor	3	3	2	**0.89**	3	**1.00**	2	3	3	**0.89**
		Availability factor	3	1	2	**0.67**	3	**1.00**	3	3	3	**1.00**
		Technical dispatchability	3	3	2	**0.89**	3	**1.00**	1	3	1	**0.56**
		Economic dispatchability	3	2	3	**0.89**	3	**1.00**	3	3	3	**1.00**
		Lifetime of global fuel reserves at current extraction rates	3	1	1	**0.56**	3	**1.00**	3	3	2	**0.89**
	Technological Lock-in	Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/thermochemical H_2 production) and operational lifetime	3	3	2	**0.89**	3	**1.00**	1	2	1	**0.44**
	Immediacy	Time to plant start-up from start of construction	3	1	2	**0.67**	2	**0.67**	3	3	2	**0.89**
	Levelised Cost of Generation	Capital costs	3	2	3	**0.89**	3	**1.00**	3	3	3	**1.00**
		Operation and maintenance costs	3	2	3	**0.89**	3	**1.00**	3	3	3	**1.00**
		Fuel costs	3	2	3	**0.89**	3	**1.00**	3	3	3	**1.00**
		Decommissioning costs	3	2	3	**0.89**	2	**0.67**	3	3	3	**1.00**
		Total levelised cost	3	2	3	**0.89**	3	**1.00**	3	3	3	**1.00**
	Cost Variability	Fuel price sensitivity	3	2	3	**0.89**	3	**1.00**	3	3	3	**1.00**
	Financial	Financial incentives and assistance	2	3	1	**0.67**	1	**0.33**	3	3	1	**0.78**

	Incentives											
Environmental	**Material Recyclability**	Recyclability of input materials	*3*	*3*	*1*	**0.78**	*2*	**0.67**	*2*	*2*	*3*	**0.78**
	Water Eco-toxicity	Freshwater eco-toxicity potential	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Marine eco-toxicity potential	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Global Warming	Global warming potential	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Ozone Layer Depletion	Ozone depletion potential	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Acidification	Acidification potential	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Eutrophication	Eutrophication potential	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Photochemical Smog	Photochemical smog creation potential	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Land Use & Quality	Land occupation	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Greenfield land use	*3*	*3*	*2*	**0.89**	*2*	**0.67**	*2*	*3*	*1*	**0.67**
		Terrestrial eco-toxicity potential	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
Social	**Provision of Employment**	Direct employment	*3*	*2*	*2*	**0.78**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
		Total employment	*3*	*2*	*2*	**0.78**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
	Human Health Impacts	Worker injuries	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*1*	**0.67**
		Human toxicity potential (excluding radiation)	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Human health impacts from radiation	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Large Accident Risk	Fatalities due to large accidents	*3*	*1*	*1*	**0.56**	*3*	**1.00**	*2*	*1*	*1*	**0.44**
	Local Community Impacts	Proportion of staff hired from local community relative to total direct employment				**0.00**		**0.00**				**0.00**
		Spending on local suppliers relative to total annual spending				**0.00**		**0.00**				**0.00**

	Direct investment in local community as proportion of total annual profits				**0.00**		**0.00**				**0.00**
Human Rights and Corruption	Involvement of countries in the life cycle with known corruption problems				**0.00**		**0.00**				**0.00**
Energy Security	Amount of imported fossil fuel potentially avoided	*2*	*3*	*2*	**0.78**	*1*	**0.33**	*2*	*3*	*1*	**0.67**
	Diversity of fuel supply mix	*2*	*2*	*1*	**0.56**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Fuel storage capabilities (energy density)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Nuclear Proliferation	Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Intergenerational Equity	Use of abiotic resources (elements)	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Use of abiotic resources (fossil fuels)	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Volume of radioactive waste to be stored	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Volume of liquid CO_2 to be stored	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*3*	**0.89**

Table 52: Data quality scores for the offshore wind power assessment

Category	Issue addressed	Indicator	'Evidence for'				'Knowledge base'		'Evidence quality'			
			Time specificity	*Geographical specificity*	*Technological specificity*	**Normalised total**	*Completeness of data*	**Normalised total**	*Data source*	*Auditability*	*Validation*	**Normalised total**
Techno-economic	**Operability**	Capacity factor	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Availability factor	*2*	*3*	*2*	**0.78**	*2*	**0.67**	*3*	*3*	*2*	**0.89**
		Technical dispatchability	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*1*	*3*	*1*	**0.56**
		Economic dispatchability	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Lifetime of global fuel reserves at current extraction rates	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
	Technological Lock-in	Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/thermochemical H_2 production) and operational lifetime	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*1*	*2*	*1*	**0.44**
	Immediacy	Time to plant start-up from start of construction	*3*	*3*	*2*	**0.89**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
	Levelised Cost of Generation	Capital costs	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Operation and maintenance costs	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Fuel costs	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Decommissioning costs	*3*	*3*	*2*	**0.89**	*2*	**0.67**	*3*	*3*	*3*	**1.00**
		Total levelised cost	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
	Cost Variability	Fuel price sensitivity	*3*	*3*	*2*	**0.89**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
	Financial	Financial incentives and assistance	*2*	*3*	*2*	**0.78**	*1*	**0.33**	*3*	*3*	*1*	**0.78**

	Incentives											
Environmental	**Material Recyclability**	Recyclability of input materials	*3*	*3*	*3*	**1.00**	*2*	**0.67**	*2*	*2*	*3*	**0.78**
	Water Eco-toxicity	Freshwater eco-toxicity potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Marine eco-toxicity potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Global Warming	Global warming potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Ozone Layer Depletion	Ozone depletion potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Acidification	Acidification potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Eutrophication	Eutrophication potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Photochemical Smog	Photochemical smog creation potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Land Use & Quality	Land occupation	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Greenfield land use	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*1*	*3*	*1*	**0.56**
		Terrestrial eco-toxicity potential	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
Social	**Provision of Employment**	Direct employment	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
		Total employment	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
	Human Health Impacts	Worker injuries	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*3*	*3*	*1*	**0.78**
		Human toxicity potential (excluding radiation)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
		Human health impacts from radiation	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Large Accident Risk	Fatalities due to large accidents	*3*	*2*	*1*	**0.67**	*3*	**1.00**	*1*	*1*	*1*	**0.33**
	Local Community Impacts	Proportion of staff hired from local community relative to total direct employment				**0.00**		**0.00**				**0.00**
		Spending on local suppliers relative to total annual spending				**0.00**		**0.00**				**0.00**

	Direct investment in local community as proportion of total annual profits				**0.00**		**0.00**				**0.00**
Human Rights and Corruption	Involvement of countries in the life cycle with known corruption problems				**0.00**		**0.00**				**0.00**
Energy Security	Amount of imported fossil fuel potentially avoided	*2*	*3*	*2*	**0.78**	*1*	**0.33**	*2*	*3*	*1*	**0.67**
	Diversity of fuel supply mix	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Fuel storage capabilities (energy density)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Nuclear Proliferation	Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Intergenerational Equity	Use of abiotic resources (elements)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Use of abiotic resources (fossil fuels)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*2*	*2*	*3*	**0.78**
	Volume of radioactive waste to be stored	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Volume of liquid CO_2 to be stored	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*3*	**0.89**

Table 53: Data quality scores for the solar photovoltaics assessment

Category	Issue addressed	Indicator	'Evidence for'				'Knowledge base'		'Evidence quality'			
			Time specificity	*Geographical specificity*	*Technological specificity*	**Normalised total**	*Completeness of data*	**Normalised total**	*Data source*	*Auditability*	*Validation*	**Normalised total**
Techno-economic	**Operability**	Capacity factor	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Availability factor	*2*	*2*	*1*	**0.56**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Technical dispatchability	*3*	*3*	*1*	**0.78**	*3*	**1.00**	*1*	*3*	*1*	**0.56**
		Economic dispatchability	*3*	*2*	*1*	**0.67**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Lifetime of global fuel reserves at current extraction rates	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
	Technological Lock-in	Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/thermochemical H_2 production) and operational lifetime	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*1*	*2*	*1*	**0.44**
	Immediacy	Time to plant start-up from start of construction	*3*	*1*	*1*	**0.56**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
	Levelised Cost of Generation	Capital costs	*3*	*2*	*1*	**0.67**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Operation and maintenance costs	*3*	*2*	*1*	**0.67**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Fuel costs	*3*	*2*	*1*	**0.67**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
		Decommissioning costs	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*3*	*3*	*3*	**1.00**
		Total levelised cost	*3*	*2*	*1*	**0.67**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
	Cost Variability	Fuel price sensitivity	*3*	*2*	*1*	**0.67**	*3*	**1.00**	*3*	*3*	*3*	**1.00**
	Financial	Financial incentives and assistance	*2*	*3*	*2*	**0.78**	*1*	**0.33**	*3*	*3*	*1*	**0.78**

	Incentives											
Environmental	**Material Recyclability**	Recyclability of input materials	*3*	*3*	*2*	**0.89**	*2*	**0.67**	*2*	*2*	*3*	**0.78**
	Water Eco-toxicity	Freshwater eco-toxicity potential	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
		Marine eco-toxicity potential	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Global Warming	Global warming potential	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Ozone Layer Depletion	Ozone depletion potential	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Acidification	Acidification potential	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Eutrophication	Eutrophication potential	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Photochemical Smog	Photochemical smog creation potential	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Land Use & Quality	Land occupation	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
		Greenfield land use	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*1*	*3*	*1*	**0.56**
		Terrestrial eco-toxicity potential	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
Social	**Provision of Employment**	Direct employment	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
		Total employment	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*2*	**0.78**
	Human Health Impacts	Worker injuries	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*3*	*3*	*1*	**0.78**
		Human toxicity potential (excluding radiation)	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
		Human health impacts from radiation	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Large Accident Risk	Fatalities due to large accidents	*3*	*1*	*2*	**0.67**	*3*	**1.00**	*1*	*1*	*1*	**0.33**
	Local Community Impacts	Proportion of staff hired from local community relative to total direct employment				**0.00**		**0.00**				**0.00**
		Spending on local suppliers relative to total annual spending				**0.00**		**0.00**				**0.00**

	Direct investment in local community as proportion of total annual profits				**0.00**		**0.00**				**0.00**
Human Rights and Corruption	Involvement of countries in the life cycle with known corruption problems				**0.00**		**0.00**				**0.00**
Energy Security	Amount of imported fossil fuel potentially avoided	*2*	*3*	*2*	**0.78**	*1*	**0.33**	*2*	*3*	*1*	**0.67**
	Diversity of fuel supply mix	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Fuel storage capabilities (energy density)	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Nuclear Proliferation	Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
Intergenerational Equity	Use of abiotic resources (elements)	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Use of abiotic resources (fossil fuels)	*3*	*2*	*3*	**0.89**	*3*	**1.00**	*3*	*2*	*3*	**0.89**
	Volume of radioactive waste to be stored	*3*	*3*	*3*	**1.00**	*3*	**1.00**	*3*	*3*	*1*	**0.78**
	Volume of liquid CO_2 to be stored	*3*	*2*	*1*	**0.67**	*2*	**0.67**	*2*	*3*	*3*	**0.89**

16 Appendix 5: Present-day electricity mix results

16.1 Techno-economic results (per year)

	Contribution from					Total value for electricity mix
	Coal	Gas	Nuclear	Wind	Solar	
1. Capacity factor (%)	1.895E+01	2.908E+01	1.707E+01	8.114E-01	5.000E-04	6.592E+01
2. Availability factor (%)	2.649E+01	4.151E+01	1.792E+01	2.201E+00	5.575E-03	8.812E+01
3. Technical dispatch. (no units)	1.420E+00	3.589E+00	2.344E+00	4.327E-01	9.302E-04	7.787E+00
4. Economic dispatch. (no units)	1.730E+01	7.977E+00	1.592E+01	2.025E+00	5.446E-03	4.323E+01
5. Lifetime of fuel reserves (yrs)	3.619E+01	2.939E+01	1.607E+01	2.705E+01	5.814E-02	1.087E+02
6. Technological lock-in resistance (yrs^{-1})	2.703E+00	7.487E+00	3.354E-01	0.000E+00	0.000E+00	1.053E+01
7. Time to start-up (months)	1.703E+01	1.755E+01	1.366E+01	3.462E-01	5.814E-06	4.858E+01
8. Levelised cost: capital (£)	4.832E+09	1.969E+09	5.659E+09	1.111E+09	1.019E+07	1.358E+10
9. Levelised cost: O&M (£)	1.365E+09	1.055E+09	1.079E+09	3.729E+08	6.871E+05	3.872E+09
10. Levelised cost: fuel (£)	2.296E+09	8.526E+09	3.999E+08	0.000E+00	0.000E+00	1.122E+10
11. Levelised cost: TOTAL (£)	8.493E+09	1.155E+10	7.138E+09	1.484E+09	1.088E+07	2.868E+10
12. Fuel price sensitivity (%)	8.221E+00	3.454E+01	1.125E+00	0.000E+00	0.000E+00	4.389E+01
13. Financial incentives (£)	0.000E+00	0.000E+00	3.830E+08	8.377E+08	8.856E+06	1.230E+09

16.2 Environmental results (per year)

	Contribution from					**Total value for electricity mix**
	Coal	Gas	Nuclear	Wind	Solar	
14. Recyclability (ratio)	2.563E-01	4.179E-01	1.631E-01	2.688E-02	5.802E-05	8.643E-01
15. Freshwater eco-toxicity (kg DCB eq.)	1.913E+09	4.526E+08	1.589E+09	2.176E+08	3.809E+05	4.173E+09
16. Marine eco-toxicity (kg DCB eq.)	6.605E+13	1.244E+12	3.031E+12	4.713E+11	1.913E+09	7.080E+13
17. Global warming (kg CO_2 eq.)	1.225E+11	6.662E+10	4.708E+08	1.138E+08	1.917E+06	1.897E+11
18. Ozone layer depletion (kg CFC-11 eq.)	4.858E+02	2.225E+03	4.082E+01	6.056E+00	3.821E-01	2.758E+03
19. Acidification (kg SO_2 eq.)	2.029E+08	2.603E+07	3.319E+06	8.423E+05	9.514E+03	2.331E+08
20. Eutrophication (kg PO_4^{3-} eq.)	2.451E+07	1.096E+07	9.989E+05	6.103E+05	1.500E+03	3.708E+07
21. Photochemical smog (kg C_2H_4 eq.)	1.601E+07	4.798E+06	3.742E+05	8.623E+04	1.468E+03	2.127E+07
22. Land occupation (m^2yr)	3.120E+09	1.113E+08	4.140E+07	3.800E+06	1.085E+05	3.276E+09
23. Greenfield land use (ratio)	7.602E-02	0.000E+00	1.757E-01	0.000E+00	0.000E+00	2.518E-01
24. Terrestrial eco-toxicity (kg DCB eq.)	1.751E+08	2.772E+07	5.584E+07	1.455E+07	2.062E+04	2.732E+08

16.3 Social results (per year)

	Contribution from					**Total value for electricity mix**
	Coal	Gas	Nuclear	Wind	Solar	
25. Direct employment (person-yrs)	6.346E+03	4.684E+03	4.218E+03	3.155E+03	1.173E+01	1.841E+04
26. Total employment (person-yrs)	2.184E+04	1.097E+04	6.099E+03	3.739E+03	1.425E+01	4.266E+04
27. Worker injuries (injuries)	5.135E+02	9.502E+01	4.463E+01	2.341E+01	1.058E-01	6.766E+02
28. Human toxicity potential (kg DCB eq.)	8.873E+09	9.563E+08	8.659E+09	7.473E+08	1.844E+06	1.924E+10
29. Health impacts from radiation (DALY)	8.116E+01	4.630E+01	1.529E+03	4.381E-01	4.342E-02	1.657E+03
30. Large accident fatalities (fatalities)	2.360E+00	8.933E-01	9.228E-05	7.847E-03	2.493E-05	3.261E+00
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe)	0.000E+00	0.000E+00	1.510E+07	2.033E+06	4.370E+03	1.714E+07
36. Diversity of fuel supply (dimensionless)	2.148E+01	4.071E+01	1.686E+01	2.705E+00	5.814E-03	8.177E+01
37. Fuel storage capabilities (GJ/m^3)	6.436E+00	1.675E-02	2.082E+06	0.000E+00	0.000E+00	2.082E+06
38. Nuclear proliferation (ordinal scale)	0.000E+00	0.000E+00	6.628E+00	0.000E+00	0.000E+00	6.628E+00
39. Depletion of elements (kg Sb eq.)	1.111E+04	4.972E+03	3.579E+03	8.521E+03	2.680E+02	2.845E+04
40. Depletion of fossil fuels (MJ)	1.730E+12	1.011E+12	6.088E+09	1.387E+09	2.387E+07	2.748E+12
41. Volume of radwaste to be stored (m^3)	0.000E+00	0.000E+00	7.663E+02	0.000E+00	0.000E+00	7.663E+02
42. Volume of liquid CO2 to be stored (m^3)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00

16.4 Techno-economic results (per unit of electricity generated)

	Contribution from					**Average value for electricity mix**
	Coal	Gas	Nuclear	Wind	Solar	
1. Capacity factor (%)	1.895E+01	2.908E+01	1.707E+01	8.114E-01	5.000E-04	6.592E+01
2. Availability factor (%)	2.649E+01	4.151E+01	1.792E+01	2.201E+00	5.575E-03	8.812E+01
3. Technical dispatch. (no units)	1.420E+00	3.589E+00	2.344E+00	4.327E-01	9.302E-04	7.787E+00
4. Economic dispatch. (no units)	1.730E+01	7.977E+00	1.592E+01	2.025E+00	5.446E-03	4.323E+01
5. Lifetime of fuel reserves (yrs)	3.619E+01	2.939E+01	1.607E+01	2.705E+01	5.814E-02	1.087E+02
6. Technological lock-in resistance (yrs^{-1})	2.703E+00	7.487E+00	3.354E-01	0.000E+00	0.000E+00	1.053E+01
7. Time to start-up (months)	1.703E+01	1.755E+01	1.366E+01	3.462E-01	5.814E-06	4.858E+01
8. Levelised cost: capital (£/MWh)	1.286E+01	5.241E+00	1.506E+01	2.959E+00	2.713E-02	3.615E+01
9. Levelised cost: O&M (£/MWh)	3.634E+00	2.808E+00	2.872E+00	9.926E-01	1.829E-03	1.031E+01
10. Levelised cost: fuel (£/MWh)	6.112E+00	2.270E+01	1.065E+00	0.000E+00	0.000E+00	2.987E+01
11. Levelised cost: TOTAL (£/MWh)	2.261E+01	3.074E+01	1.900E+01	3.951E+00	2.895E-02	7.633E+01
12. Fuel price sensitivity (%)	8.221E+00	3.454E+01	1.125E+00	0.000E+00	0.000E+00	4.389E+01
13. Financial incentives (£/MWh)	0.000E+00	0.000E+00	1.020E+00	2.230E+00	2.357E-02	3.273E+00

16.5 Environmental results (per unit of electricity generated)

	Contribution from					**Average value for electricity mix**
	Coal	Gas	Nuclear	Wind [315]	Solar	
14. Recyclability (ratio)	2.563E-01	4.179E-01	1.631E-01	2.688E-02	5.796E-05	8.643E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	5.092E-03	1.205E-03	4.230E-03	5.793E-04	1.014E-06	1.111E-02
16. Marine eco-toxicity (kg DCB eq. /kWh)	1.758E+02	3.312E+00	8.067E+00	1.254E+00	5.091E-03	1.885E+02
17. Global warming (kg CO_2 eq. /kWh)	3.260E-01	1.773E-01	1.253E-03	3.030E-04	5.103E-06	5.049E-01
18. Ozone layer depletion (kg CFC-11 eq. /kWh)	1.293E-09	5.922E-09	1.087E-10	1.612E-11	1.017E-12	7.341E-09
19. Acidification (kg SO_2 eq. /kWh)	5.402E-04	6.928E-05	8.836E-06	2.242E-06	2.532E-08	6.206E-04
20. Eutrophication (kg PO_4^{3-} eq. /kWh)	6.524E-05	2.916E-05	2.659E-06	1.624E-06	3.992E-09	9.869E-05
21. Photochemical smog (kg C_2H_4 eq. /kWh)	4.261E-05	1.277E-05	9.962E-07	2.295E-07	3.907E-09	5.661E-05
22. Land occupation (m^2yr/kWh)	8.304E-03	2.963E-04	1.102E-04	1.012E-05	2.888E-07	8.721E-03
23. Greenfield land use (ratio)	7.602E-02	0.000E+00	1.757E-01	0.000E+00	0.000E+00	2.518E-01
24. Terrestrial eco-toxicity (kg DCB eq. /kWh)	4.660E-04	7.378E-05	1.486E-04	3.872E-05	5.488E-08	7.272E-04

16.6 Social results (per unit of electricity generated)

	Contribution from					Total value for electricity mix
	Coal	Gas	Nuclear	Wind	Solar	
25. Direct employment (person-yrs/TWh)	1.689E+01	1.247E+01	1.123E+01	8.398E+00	3.124E-02	4.902E+01
26. Total employment (person-yrs/TWh)	5.813E+01	2.920E+01	1.624E+01	9.952E+00	3.795E-02	1.136E+02
27. Worker injuries (injuries/TWh)	1.367E+00	2.529E-01	1.188E-01	6.231E-02	2.816E-04	1.801E+00
28. Human toxicity potential (kg DCB eq./kWh)	2.362E-02	2.546E-03	2.305E-02	1.989E-03	4.910E-06	5.121E-02
29. Health impacts from radiation (DALY/kWh)	2.160E-10	1.232E-10	4.069E-09	1.166E-12	1.156E-13	4.410E-09
30. Large accident fatalities (fatalities/PWh)	6.283E+00	2.378E+00	2.456E-04	2.089E-02	6.637E-05	8.682E+00
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	0.000E+00	0.000E+00	4.019E-05	5.412E-06	1.163E-08	4.561E-05
36. Diversity of fuel supply (dimensionless)	2.148E+01	4.071E+01	1.686E+01	2.705E+00	5.814E-03	8.177E+01
37. Fuel storage capabilities (GJ/m^3)	6.436E+00	1.675E-02	2.082E+06	0.000E+00	0.000E+00	2.082E+06
38. Nuclear proliferation (ordinal scale)	0.000E+00	0.000E+00	6.628E+00	0.000E+00	0.000E+00	6.628E+00
39. Depletion of elements (kg Sb eq./kWh)	2.956E-08	1.324E-08	9.526E-09	2.268E-08	7.133E-10	7.572E-08
40. Depletion of fossil fuels (MJ/kWh)	4.605E+00	2.691E+00	1.621E-02	3.693E-03	6.355E-05	7.316E+00
41. Volume of radwaste to be stored (m^3/TWh)	0.000E+00	0.000E+00	2.040E+00	0.000E+00	0.000E+00	2.040E+00
42. Volume of liquid CO2 to be stored (m^3/TWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00

17 Appendix 6: Derivation of future cost estimates using learning curves

Wind power, solar PV and coal CCS are relatively immature technologies whose uptake is expected to increase over the coming decades. As a result, the costs of these three technologies can be expected to fall significantly as their respective industries exploit standardisation, economies of scale and industrial learning. However, the extent of the improvement is highly uncertain and very few cost estimates stretch beyond the 2020-2030 time frame. Below is a description of available UK estimates followed by a speculative estimation of future costs under UK conditions using learning rates.

17.1 Relevant cost estimates available in literature

17.1.1 Available estimates for offshore wind

Mott MacDonald [201] project costs out to a 2023 start date. They differentiate between projects falling under the Round 2 wind deployment timetable and those under Round 3, with Round 3 estimates being higher due to greater distance from the shore and, generally, deeper waters. Round 2 projects beginning in 2013 are estimated to cost £146.1/MWh, assuming a 22 year lifetime, 37% capacity factor and 10% discount rate (see Table 54). The corresponding estimate for Round 3 projects is £174.6/MWh, using the same assumptions. In 2023, these figures reduce to £111.5/MWh (Round 2) and £126.9/MWh (Round 3), both assuming slightly longer lifetimes of 24 years, capacity factors of 39% and 10% discount.

Arup have published cost estimates for renewables in the UK out to 2030 [333]. Their best estimate for a Round 2 project in 2015 is £147/MWh, assuming a lifetime of 24 years, capacity factor of 38% and a discount rate of 11.6% (see Table 54). This is very similar to the Mott MacDonald estimate. A Round 3 project in the same time frame is expected to cost £198/MWh, assuming a lifetime of 22 years, capacity factor of 38% and a discount rate of 13.2%. This is higher than the corresponding Mott MacDonald figure, but the extra discounting may be partly responsible, as this has the effect of increasing the levelised cost of capital intensive projects. By 2030, the cost of Round 2 wind has reduced to £104/MWh, but this time the discount rate used is

9.6%. Round 3 has reduced to £121/MWh, also at a 9.6% discount rate. These figures cannot be compared to Mott MacDonald as they are further into the future, but extrapolating the Mott MacDonald figures forward shows reasonable agreement. Looking at Arup's cost estimates over time, however, shows a particularly steep decline in costs; significantly steeper than the Mott MacDonald estimates. This can be explained in part by the declining discount rates Arup applies over time: on top of the cost reduction due to learning, apparent cost also declines as discounting falls from 11.6 to 9.6% in the case of Round 2 and 13.2 to 9.6% for Round 3. It is also of note that the learning rate adopted by Arup is, at 12%, higher than that suggested by the IEA [356] (although it does match the Carbon Trust's base case [333]).

Table 54: UK offshore wind cost estimates from 2009 to 2030, £/MWh

Round 2	Mott MacDonald 2010 [201]			Arup 2011 [333]			UKERC 2010 [372]		
	low	*central / average*	*high*	*low*	*central*	*high*	*low*	*central*	*high*
2009/10	148.5	154.7	160.9	155	174	196	-	-	-
2013	-	146.1	-	-	-	-	-	-	-
2015	-	-	-	131	147	167	-	-	-
2017	112.4	128.9	145.4	-	-	-	-	-	-
2020	-	-	-	106	117	132	-	-	-
2023	-	111.5	-	-	-	-	-	-	-
2025	-	-	-	99	110	123	95	116	185
2030	-	-	-	93	104	116	-	-	-

Round 3	Mott MacDonald 2010 [201]			Arup 2011 [333]		
	low	*central / average*	*high*	*low*	*central*	*high*
2009/2010	177.4	183.95	190.5	-	-	-
2013	-	174.6	-	-	-	-
2015	-	-	-	147	198	231
2017	127.9	150.4	172.9	-	-	-
2020	-	-	-	117	156	180
2023	-	126.9	-	-	-	-
2025	-	-	-	110	142	164
2030	-	-	-	104	121	138

Finally, UKERC have also published future offshore wind cost estimates [372]. They begin in the present day (2010) using an estimate of £145/MWh at 10% discount rate, derived from a literature review. The review includes the Mott MacDonald figures discussed above, hence the close match to their Round 2 estimate of £146.1/MWh. However, UKERC ignore any Round 3 estimates. Given the fact that their analysis for future dates is then based on this Round 2 starting figure, their central estimate of £116/MWh for the year 2025 is arguably too low, as by this time Round 3 (with its higher costs) will dominate offshore build. The authors do, however, address the extra costs of Round 3 using sensitivity analysis, arriving at an absolute worst case estimate of £185/MWh in 2025 at 10% discount (see Table 54). Their various sensitivity analyses highlight the great uncertainty involved in the problem, giving a potential range of £95-185/MWh. The central estimate of £116/MWh assumes a 20 year lifetime and 38% capacity factor.

17.1.2 Available estimates for PV

The study by Arup discussed above also includes levelised cost estimates for PV installations. However, these are based on installations larger than 50 kWp and therefore correspond to commercial-sized projects as opposed to residential systems (typically 3 kWp). The authors acknowledge that costs for residential systems tend to be higher, principally because domestic buyers are unable to negotiate the lower prices that bulk-buying allows [333]. Arup estimates a cost in 2015 of £228/MWh, assuming a 25 year lifetime, 11% capacity factor and 7.5% discount rate (see Table 55). This decreases to £150/MWh by 2030 under the same assumptions. The high capacity factor (11%) and low discount rate (7.5%) will both have the effect of the reducing the estimated cost, further distancing this result from the higher cost that might be expected for a residential system.

Table 55: UK solar photovoltaics cost estimates from 2010 to 2030, £/MWh

>50 kWp	Arup 2011 [333]		
	low	*central / average*	*high*
2010	202	282	380
2015	165	228	306
2020	136	187	250
2025	120	164	218
2030	111	150	199

17.1.3 Available estimates for coal CCS

The aforementioned study by Mott MacDonald includes estimates of coal CCS costs out to 2023, distinguishing between the main competing technologies: pulverised coal plants with post-combustion CO_2 capture (PC CCS) and integrated gasification combined cycle plants with pre-combustion CO_2 capture (IGCC CCS). PC CCS projects beginning in 2013 are expected to cost £125.40/MWh excluding carbon tax, assuming 10% discount rate, 36 year lifetime, 76% capacity factor and 90% CO_2 removal efficiency (see Table 56). At the same discount rate and with the same CO_2 removal efficiency, IGCC CCS will cost £133.80/MWh, assuming a 25 year lifetime and 78% capacity factor. By 2023, the cost of PC CCS has decreased to £99.90/MWh, along with capacity factor improvements to 80% and a lifetime of 38 years. In the same time period, IGCC CCS would be slightly cheaper at £96.10/MWh with a 79% capacity factor and a 30 year life.

Table 56: Coal CCS cost estimates from 2009 to 2050, £/MWh

PC CCS	Mott MacDonald 2010 [201]			van den Broek et al. 2009 [373]		
	low	*central / average*	*high*	*low*	*central*	*high*
2009/10	129.7	132.7	135.6	33.5	36.3	39.0
2013	-	125.4	-	-	-	-
2017	91.1	108.1	125.1	-	-	-
2020	-	-	-	30.1	34.2	38.3
2023	-	99.9	-	-	-	-
2030	-	-	-	28.7	33.5	37.6
2040	-	-	-	24.6	30.1	36.3
2050	-	-	-	23.3	28.7	34.9

IGCC CCS	Mott MacDonald 2010 [201]			van den Broek et al. 2009 [373]		
	low	*central / average*	*high*	*low*	*central*	*high*
2009/10	137.5	139.8	142.1	33.5	34.9	36.9
2013	-	133.8	-	-	-	-
2017	87.8	109.8	131.8	-	-	-
2020	-	-	-	24.6	28.0	32.8
2023	-	96.1	-	-	-	-
2030	-	-	-	20.5	25.3	31.5
2040	-	-	-	19.2	23.9	30.8
2050	-	-	-	17.8	22.6	29.4

Future coal CCS costs have also been estimated out to 2050 by van den Broek et al. [373], although not specifically for the UK. Their results are shown in Table 56, converted from 2005 euros to pound sterling using an exchange rate of 0.684 (the average for the year 2005 [calculated from 374]). At 10% discount rate, costs of PC CCS decline from £36.30/MWh in the present day to £28.70/MWh in 2050, while IGCC CCS reduces from £34.90 to £22.60/MWh. Clearly these estimates are far lower than those of Mott MacDonald, however this appears to be due simply to a lower starting cost; the authors acknowledge that the results “are sensitive to the baseline input data which, for example, did not include recent price increases”. This, coupled with the high cost of construction in the UK, explains the difference in starting cost. In fact, the rate of cost reduction in van den Broek’s analysis is more conservative than that of Mott

MacDonald: the cost of PC CCS, for example, decreases by 21% over 40 years compared to 25% over just 14 years in the case of Mott MacDonald. The faster reduction in the Mott MacDonald report appears to be due to an assumption of rapid uptake, meaning the cost premium associated with first-of-a-kind installations is entirely eliminated by the early 2020s.

17.2 Predicting future costs of offshore wind, PV and coal CCS

Future costs in this study have been estimated using a simplistic approach, in which present day levelised costs are reduced over time using learning rates and projected global cumulative installed capacity. Inherent in this is the assumption that cost savings are accrued at equal rates for both capital and O&M expenditure, which is unlikely to be true. However, this is considered to be a reasonable assumption given the following:

1. The costs of wind power and photovoltaics are almost entirely dominated by capital costs, meaning savings made due to O&M are less significant regardless of their learning rate.
2. The learning rates used for coal CCS in this study are taken from Rubin et al. [357], in which learning rates are calculated specifically for total levelised costs, taking into account separate rates for capital and operational costs. The resulting rates are therefore intended for exactly the approach taken here.
3. Learning rates are highly uncertain, being based both on historical trends and perception of the potential for future progress. They also assume that learning takes place at a constant rate, which may not be true: cost trends may in fact follow an S-shaped curve in which learning is initially slow, then quick, then slow again as technology matures [357]. Moreover, central to the estimation of future costs is the assumed rate of global capacity increase, which itself is extremely uncertain. Given these unavoidable uncertainties, there seems little benefit in further increasing the complexity of the analysis.

17.2.1 Offshore wind

In this analysis, only Round 3 cost estimates are taken as a starting point. This is because Round 3 represents the vast majority of future build opportunities, totalling 33 GW capacity compared to 8 GW for Rounds 1 and 2 combined [364]; Triton Knoll is the final (and largest) Round 2 project and will be completed in 2021, by which time some Round 3 projects should already have been generating electricity for several years, such as the Atlantic Array [314].

For offshore wind, the Mott MacDonald average 2009 cost of £183.95/MWh (10% discount) was used as a starting point. Learning rates of 9% and 12% were applied, according to the IEA [356] and Arup/Carbon Trust [333], respectively. Global installed capacity projections were taken from the IEA's technology roadmap [375], using a 2010 capacity of 194.4 GW as a starting point [376]. The IEA capacity projections only run to 2050, so figures for 2060 and 2070 were extrapolated linearly. Both onshore and offshore wind were included in current and future installed capacity estimates given their technological similarity. It is acknowledged that this may lead to future costs being overestimated as offshore wind will likely be deployed at a faster rate than onshore. Results are therefore conservative.

The results are shown in Figure 65, along with the assumed cumulative global capacity in the same period. Costs are shown to decline from £184/MWh in the present to £127 or £112/MWh in 2070, depending on the learning rate. Estimates for the available years by Arup and Mott MacDonald (2009 to 2030) are also included in Figure 65 for comparison; they show faster cost reduction than in this study, which seems mainly due to the conservatism mentioned above. The 12% learning rate is taken as the 'best estimate' for use in this study, as a reflection of the fact that, (a) the UK is currently the world leader in deployment of offshore wind, and can therefore expect high learning rates, and (b) offshore wind is a less mature technology than onshore wind, so the installed capacity figures used here underestimate the growth of the offshore sector.

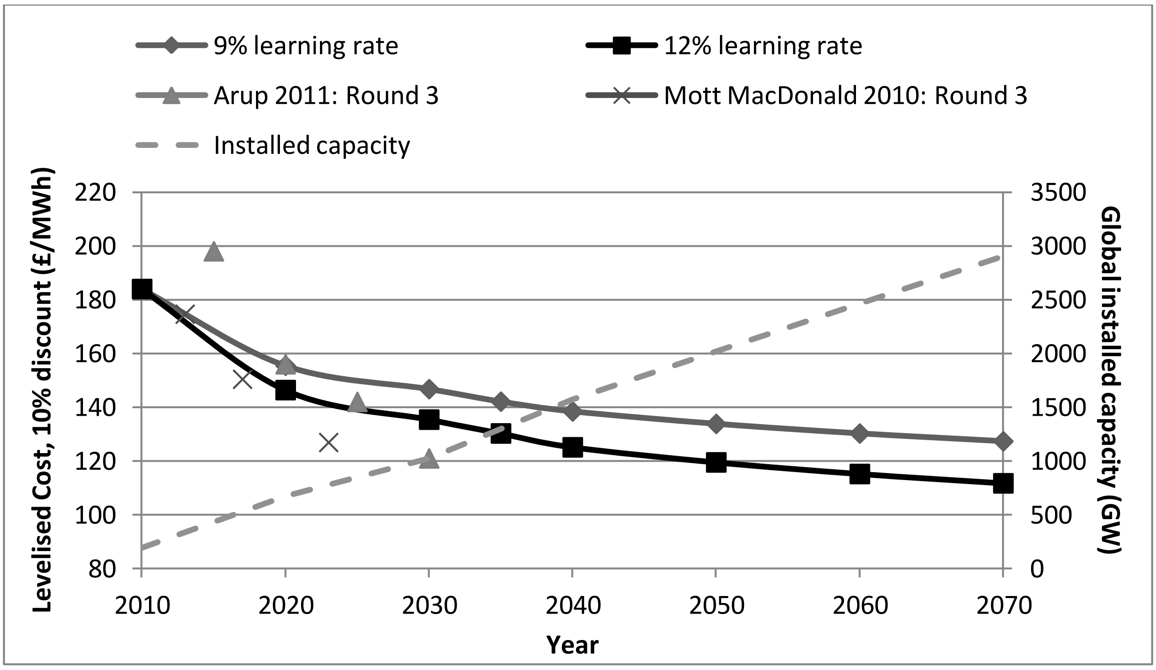


Figure 65: Estimated levelised cost of offshore wind power from 2010 to 2070, using both a 9% and 12% learning rate

17.2.2 Solar photovoltaics

The present-day costs of residential PV are highly debatable, making it difficult to select a starting point for future cost estimation. According to IEA data [99], using only OECD installations and a discount rate of 10%, the average cost is £302/MWh ($553/MWh), with a range of £182-510/MWh. However, this is based on 12 installations of which only four are smaller than 50 kWp (a residential installation is typically 3 or 4 kWp). Since larger projects benefit from economies of scale and the ability to negotiate lower prices, this figure underestimates the cost of residential systems. Indeed, if the four smaller systems are isolated, the average cost is £391/MWh with a range of £278-510/MWh. Moreover, all these installations have an estimated capacity factor of 10-13%, which is high for the UK given our low insolation: residential output for a good system is generally expected to be 700-800 kWh/kWp/yr [329, 330], which equates to 8-9.1% capacity factor. If the undiscounted costs of the four IEA installations are discounted with a capacity factor of 9% in place of the original higher percentage, the average cost becomes £465/MWh with a range of £296-598/MWh.

This cost seems high, particularly when compared to the 2010 Arup estimate of £282/MWh [333]. However, as discussed above, that estimate is discounted at 7.5%, has a capacity factor of 11% and describes systems larger than 50 kWp, all of which decrease the cost relative to a normal residential system at 10% discount rate. However, Arup do provide undiscounted costs for smaller installations. Levelising these costs, assuming 10% discount rate and 9% capacity factor, yields a median of £498/MWh with a range of £403-800/MWh. This median cost was used as the 'best estimate' and starting point for future cost estimation due to the fact that it is UK-specific (whereas the IEA estimates discussed above are not).

The IEA suggests a learning rate of 18% for solar PV, with global installed capacity of residential PV growing from 17 GW in 2010 to 1380 GW in 2050 [353]. As with the offshore wind estimates, capacity projection beyond 2050 were extrapolated linearly. Clearly, given the various estimates of present day PV costs discussed above, several permutations of the results are possible. These are shown in Figure 66, along with the assumed cumulative global capacity in the same period. The series entitled "Arup 2011, <50 kWp, UK capacity factor" is the 'best estimate', as discussed in the previous paragraph, starting in the present day at £498/MWh and ending in 2070 at £123/MWh.

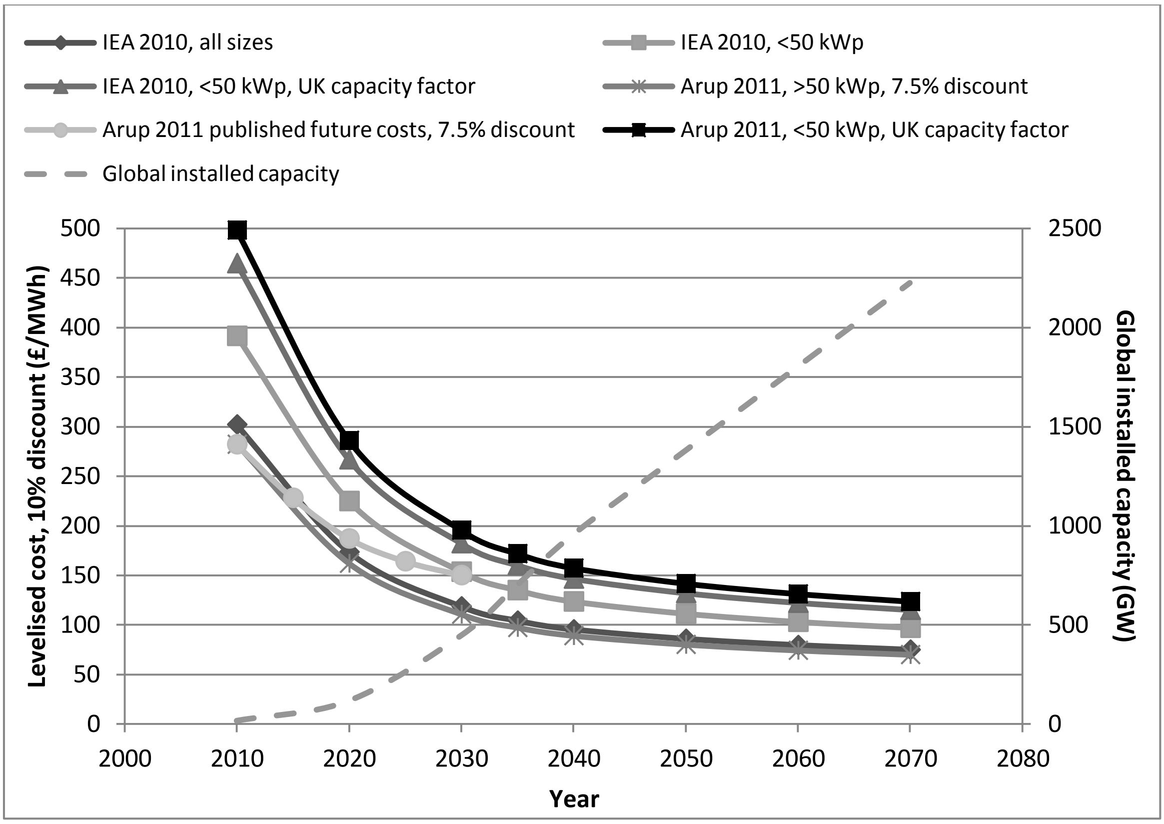


Figure 66: Estimated levelised cost of residential solar PV from 2010 to 2070, 18% learning rate

17.2.3 Coal CCS

The starting cost of pulverised coal CCS (PC CCS) is taken to be £132.70/MWh, as given in Mott MacDonald for the year 2009 [201]. The equivalent cost from the same study is taken as the starting point for integrated gasification combined cycle CCS (IGCC CCS): £139.80/MWh. Learning rates of 3.5% and 4.9% were applied to PC CCS and IGCC CCS, respectively, as suggested by Rubin et al. [357]. Global installed capacity projections were taken from the relevant IEA Technology Roadmap [377], consistent with the approach taken with offshore wind and photovoltaics. However, in this case the IEA only give installed capacities of coal CCS in the years 2020 and 2050, meaning estimates for other years had to be interpolated or extrapolated. This was achieved on a linear basis rather than exponential since the IEA anticipate small-scale demonstration plants making up capacity until 2020, followed by a period of much quicker, sustained expansion as large-scale commercial plants are steadily deployed. There is also difficulty in assigning a value to current installed capacity: the value is in fact zero, since no commercial CCS power plants exist. However, the components required (carbon capture equipment and combustion plants based on traditional coal or CCGT plants) are relatively widespread, meaning assigning a value of zero is inappropriate. Rubin et al. [357] suggest equivalent installed capacities of 5 and 7 GW for PC CCS and IGCC CCS respectively. In the absence of other information, those values were adopted here.

The results are shown in Figure 67 along with the available future estimates by Mott MacDonald and van den Broek et al. [373] discussed in the preceding sections. All estimates agree that IGCC CCS will become cheaper than PC CCS as capacity increases, however the absolute values and the rates of cost decrease do not necessarily agree for reasons discussed in the earlier sections (namely, Mott MacDonald expect quick, widespread deployment, while van den Broek et al. underestimate the present day cost of generation).

It is of note that the curves for IGCC CCS and PC CCS resulting from this study are not smooth: there is a change after 2030, resulting from the somewhat unrealistic shape of the global installed capacity curve given the linearity assumption mentioned above. In reality costs can be expected to decline more smoothly while still following the trend of rapid initial reduction during the demonstration phase followed by slower reduction as installed capacities increase.

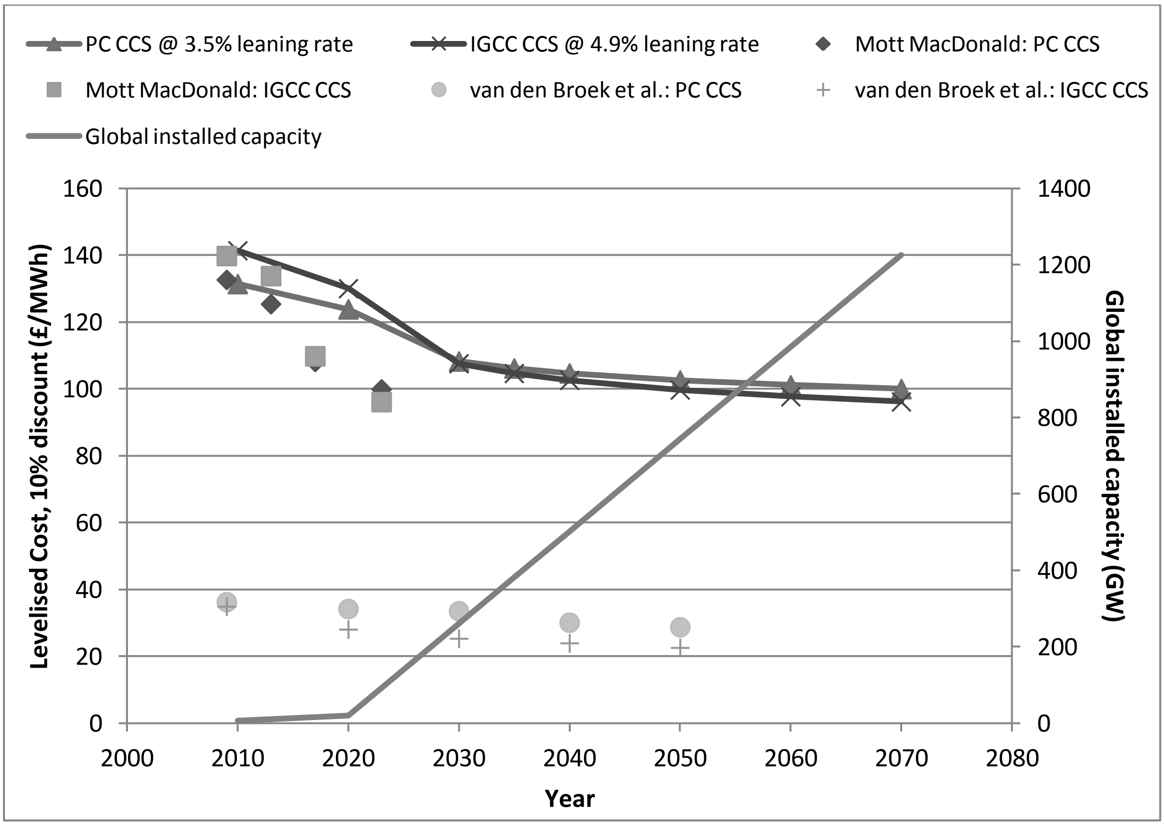


Figure 67: Estimated levelised cost of PC CCS and IGCC CCS from 2010 to 2070

18 Appendix 7: Future indicator results, by technology

18.1 Nuclear power

18.1.1 Techno-economic results

	2020	2035	2050	2070
1. Capacity factor (%)	8.500E+01	8.500E+01	8.500E+01	8.500E+01
2. Availability factor (%)	8.921E+01	8.921E+01	8.921E+01	8.921E+01
3. Technical dispatch. (no units)	1.067E+01	1.067E+01	1.067E+01	1.067E+01
4. Economic dispatch. (no units)	7.611E+01	7.611E+01	7.611E+01	7.611E+01
5. Lifetime of fuel reserves (yrs)	7.000E+01	5.500E+01	4.000E+01	2.000E+01
6. Technological lock-in resistance (yrs^{-1})	1.670E+00	1.670E+00	1.670E+00	1.670E+00
7. Time to start-up (months)	6.800E+01	6.800E+01	6.800E+01	6.800E+01
8. Levelised cost: capital (£/MWh)	5.130E+01	5.130E+01	5.130E+01	5.130E+01
9. Levelised cost: O&M (£/MWh)	1.090E+01	1.090E+01	1.090E+01	1.090E+01
10. Levelised cost: fuel (£/MWh)	5.200E+00	5.200E+00	5.200E+00	5.200E+00
11. Levelised cost: TOTAL (£/MWh)	6.740E+01	6.740E+01	6.740E+01	6.740E+01
12. Fuel price sensitivity (%)	7.715E+00	7.715E+00	7.715E+00	7.715E+00
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

18.1.2 Environmental results

	2020	2035	2050	2070
14. Recyclability (ratio)	8.120E-01	8.120E-01	8.120E-01	8.120E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	2.106E-02	2.106E-02	2.106E-02	2.106E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	4.016E+01	4.016E+01	4.016E+01	4.016E+01
17. Global warming (kg CO_2 eq./kWh)	6.239E-03	6.239E-03	6.239E-03	6.239E-03
18. Ozone layer depletion (kg CFC-11 eq./kWh)	5.410E-10	5.410E-10	5.410E-10	5.410E-10
19. Acidification (kg SO_2 eq./kWh)	4.399E-05	4.399E-05	4.399E-05	4.399E-05
20. Eutrophication (kg PO_4^{3-} eq./kWh)	1.324E-05	1.324E-05	1.324E-05	1.324E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	4.960E-06	4.960E-06	4.960E-06	4.960E-06
22. Land occupation (m^2yr/kWh)	5.487E-04	5.487E-04	5.487E-04	5.487E-04
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	7.400E-04	7.400E-04	7.400E-04	7.400E-04

18.1.3 Social results

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	5.590E+01	5.590E+01	5.590E+01	5.590E+01
26. Total employment (person-yrs/TWh)	8.083E+01	8.083E+01	8.083E+01	8.083E+01
27. Worker injuries (injuries/TWh)	3.468E-01	1.945E-01	1.161E-01	1.161E-01
28. Human toxicity potential (kg DCB eq./kWh)	1.148E-01	1.148E-01	1.148E-01	1.148E-01
29. Health impacts from radiation (DALY/kWh)	2.026E-08	2.026E-08	2.026E-08	2.026E-08
30. Large accident fatalities (fatalities/PWh)	1.223E-03	1.223E-03	1.223E-03	1.223E-03
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	2.001E-04	2.001E-04	2.001E-04	2.001E-04
36. Diversity of fuel supply (dimensionless)	8.396E+01	8.396E+01	8.396E+01	8.396E+01
37. Fuel storage capabilities (GJ/m^3)	1.037E+07	1.037E+07	1.037E+07	1.037E+07
38. Nuclear proliferation (ordinal scale)	3.300E+01	3.300E+01	3.300E+01	3.300E+01
39. Depletion of elements (kg Sb eq./kWh)	4.743E-08	4.743E-08	4.743E-08	4.743E-08
40. Depletion of fossil fuels (MJ/kWh)	8.068E-02	8.068E-02	8.068E-02	8.068E-02
41. Volume of radwaste to be stored (m^3/TWh)	1.016E+01	1.016E+01	1.016E+01	1.016E+01
42. Volume of liquid CO_2 to be stored (m^3/MWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00

18.2 Natural gas power

18.2.1 Techno-economic results

	2020	2035	2050	2070
1. Capacity factor (%)	6.215E+01	6.215E+01	6.215E+01	6.215E+01
2. Availability factor (%)	8.870E+01	8.870E+01	8.870E+01	8.870E+01
3. Technical dispatch. (no units)	8.330E+00	8.330E+00	8.330E+00	8.330E+00
4. Economic dispatch. (no units)	1.635E+01	1.635E+01	1.635E+01	1.635E+01
5. Lifetime of fuel reserves (yrs)	5.280E+01	3.780E+01	2.280E+01	2.800E+00
6. Technological lock-in resistance (yrs^{-1})	1.600E+01	1.600E+01	1.600E+01	1.600E+01
7. Time to start-up (months)	3.750E+01	3.750E+01	3.750E+01	3.750E+01
8. Levelised cost: capital (£/MWh)	1.110E+01	1.110E+01	1.110E+01	1.110E+01
9. Levelised cost: O&M (£/MWh)	6.000E+00	6.000E+00	6.000E+00	6.000E+00
10. Levelised cost: fuel (£/MWh)	5.090E+01	5.090E+01	5.090E+01	5.090E+01
11. Levelised cost: TOTAL (£/MWh)	6.790E+01	6.790E+01	6.790E+01	6.790E+01
12. Fuel price sensitivity (%)	7.496E+01	7.496E+01	7.496E+01	7.496E+01
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

18.2.2 Environmental results

	2020	2035	2050	2070
14. Recyclability (ratio)	8.930E-01	8.930E-01	8.930E-01	8.930E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	2.575E-03	2.575E-03	2.575E-03	2.575E-03
16. Marine eco-toxicity (kg DCB eq./kWh)	7.077E+00	7.077E+00	7.077E+00	7.077E+00
17. Global warming (kg CO_2 eq./kWh)	3.790E-01	3.790E-01	3.790E-01	3.790E-01
18. Ozone layer depletion (kg CFC-11 eq./kWh)	1.266E-08	1.266E-08	1.266E-08	1.266E-08
19. Acidification (kg SO_2 eq./kWh)	1.480E-04	1.480E-04	1.480E-04	1.480E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	6.232E-05	6.232E-05	6.232E-05	6.232E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	2.729E-05	2.729E-05	2.729E-05	2.729E-05
22. Land occupation (m^2yr/kWh)	6.331E-04	6.331E-04	6.331E-04	6.331E-04
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	1.577E-04	1.577E-04	1.577E-04	1.577E-04

18.2.3 Social results

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	2.664E+01	2.664E+01	2.664E+01	2.664E+01
26. Total employment (person-yrs/TWh)	6.241E+01	6.241E+01	6.241E+01	6.241E+01
27. Worker injuries (injuries/TWh)	2.875E-01	1.339E-01	6.729E-02	6.729E-02
28. Human toxicity potential (kg DCB eq./kWh)	5.440E-03	5.440E-03	5.440E-03	5.440E-03
29. Health impacts from radiation (DALY/kWh)	2.634E-10	2.634E-10	2.634E-10	2.634E-10
30. Large accident fatalities (fatalities/PWh)	5.081E+00	3.539E+00	7.835E+00	7.835E+00
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	n/a	n/a	n/a	n/a
36. Diversity of fuel supply (dimensionless)	8.700E+01	8.700E+01	8.700E+01	8.700E+01
37. Fuel storage capabilities (GJ/m^3)	3.580E-02	3.580E-02	3.580E-02	3.580E-02
38. Nuclear proliferation (ordinal scale)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
39. Depletion of elements (kg Sb eq./kWh)	2.828E-08	2.828E-08	2.828E-08	2.828E-08
40. Depletion of fossil fuels (MJ/kWh)	5.751E+00	5.751E+00	5.751E+00	5.751E+00
41. Volume of radwaste to be stored (m^3/TWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00

18.3 Coal power

18.3.1 Techno-economic results

	2020	2035	2050	2070
1. Capacity factor (%)	6.232E+01	6.232E+01	6.232E+01	6.232E+01
2. Availability factor (%)	8.710E+01	8.710E+01	8.710E+01	8.710E+01
3. Technical dispatch. (no units)	5.000E+00	5.000E+00	5.000E+00	5.000E+00
4. Economic dispatch. (no units)	5.016E+01	5.016E+01	5.016E+01	5.016E+01
5. Lifetime of fuel reserves (yrs)	1.090E+02	9.400E+01	7.900E+01	5.900E+01
6. Technological lock-in resistance (yrs^{-1})	8.890E+00	8.890E+00	8.890E+00	8.890E+00
7. Time to start-up (months)	5.600E+01	5.600E+01	5.600E+01	5.600E+01
8. Levelised cost: capital (£/MWh)	3.070E+01	3.070E+01	3.070E+01	3.070E+01
9. Levelised cost: O&M (£/MWh)	1.075E+01	1.075E+01	1.075E+01	1.075E+01
10. Levelised cost: fuel (£/MWh)	1.975E+01	1.975E+01	1.975E+01	1.975E+01
11. Levelised cost: TOTAL (£/MWh)	6.120E+01	6.120E+01	6.120E+01	6.120E+01
12. Fuel price sensitivity (%)	3.227E+01	3.227E+01	3.227E+01	3.227E+01
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

18.3.2 Environmental results

	2020	2035	2050	2070
14. Recyclability (ratio)	8.430E-01	8.430E-01	8.430E-01	8.430E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	1.675E-02	1.675E-02	1.675E-02	1.675E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	5.782E+02	5.782E+02	5.782E+02	5.782E+02
17. Global warming (kg CO_2 eq./kWh)	1.072E+00	1.072E+00	1.072E+00	1.072E+00
18. Ozone layer depletion (kg CFC-11 eq./kWh)	4.253E-09	4.253E-09	4.253E-09	4.253E-09
19. Acidification (kg SO_2 eq./kWh)	1.777E-03	1.777E-03	1.777E-03	1.777E-03
20. Eutrophication (kg PO_4^{3-} eq./kWh)	2.146E-04	2.146E-04	2.146E-04	2.146E-04
21. Photochemical smog (kg C_2H_4 eq./kWh)	1.401E-04	1.401E-04	1.401E-04	1.401E-04
22. Land occupation (m^2yr/kWh)	2.731E-02	2.731E-02	2.731E-02	2.731E-02
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	1.533E-03	1.533E-03	1.533E-03	1.533E-03

18.3.3 Social results

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	5.556E+01	5.556E+01	5.556E+01	5.556E+01
26. Total employment (person-yrs/TWh)	1.912E+02	1.912E+02	1.912E+02	1.912E+02
27. Worker injuries (injuries/TWh)	2.161E+00	9.955E-01	4.691E-01	4.691E-01
28. Human toxicity potential (kg DCB eq./kWh)	7.768E-02	7.768E-02	7.768E-02	7.768E-02
29. Health impacts from radiation (DALY/kWh)	7.105E-10	7.105E-10	7.105E-10	7.105E-10
30. Large accident fatalities (fatalities/PWh)	2.066E+01	1.176E+01	1.376E+01	1.376E+01
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a

32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	n/a	n/a	n/a	n/a
36. Diversity of fuel supply (dimensionless)	7.064E+01	7.064E+01	7.064E+01	7.064E+01
37. Fuel storage capabilities (GJ/m^3)	2.117E+01	2.117E+01	2.117E+01	2.117E+01
38. Nuclear proliferation (ordinal scale)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
39. Depletion of elements (kg Sb eq./kWh)	9.722E-08	9.722E-08	9.722E-08	9.722E-08
40. Depletion of fossil fuels (MJ/kWh)	1.514E+01	1.514E+01	1.514E+01	1.514E+01
41. Volume of radwaste to be stored (m^3/TWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00

18.4 Wind power

18.4.1 Techno-economic results

	2020	2035	2050	2070
1. Capacity factor (%)	4.000E+01	5.000E+01	5.000E+01	5.000E+01
2. Availability factor (%)	9.500E+01	9.500E+01	9.500E+01	9.500E+01
3. Technical dispatch. (no units)	1.600E+01	1.600E+01	1.600E+01	1.600E+01
4. Economic dispatch. (no units)	7.565E+01	7.488E+01	7.488E+01	7.488E+01
5. Lifetime of fuel reserves (yrs)	1.000E+03	1.000E+03	1.000E+03	1.000E+03
6. Technological lock-in resistance (yrs^{-1})	0.000E+00	0.000E+00	0.000E+00	0.000E+00
7. Time to start-up (months)	1.280E+01	1.280E+01	1.280E+01	1.280E+01
8. Levelised cost: capital (£/MWh)	9.600E+01	9.754E+01	8.948E+01	8.366E+01
9. Levelised cost: O&M (£/MWh)	3.090E+01	3.272E+01	3.002E+01	2.806E+01
10. Levelised cost: fuel (£/MWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
11. Levelised cost: TOTAL (£/MWh)	1.269E+02	1.303E+02	1.195E+02	1.117E+02
12. Fuel price sensitivity (%)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

18.4.2 Environmental results

	2020	2035	2050	2070
14. Recyclability (ratio)	9.940E-01	9.940E-01	9.940E-01	9.940E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	1.606E-02	1.078E-02	8.675E-03	8.675E-03
16. Marine eco-toxicity (kg DCB eq./kWh)	3.479E+01	2.307E+01	1.826E+01	1.826E+01
17. Global warming (kg CO_2 eq./kWh)	8.403E-03	5.731E-03	4.727E-03	4.727E-03
18. Ozone layer depletion (kg CFC-11 eq./kWh)	4.470E-10	3.064E-10	2.546E-10	2.546E-10
19. Acidification (kg SO_2 eq./kWh)	6.218E-05	4.167E-05	3.350E-05	3.350E-05
20. Eutrophication (kg PO_4^{3-} eq./kWh)	4.505E-05	2.980E-05	2.350E-05	2.350E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	6.365E-06	4.287E-06	3.472E-06	3.472E-06
22. Land occupation (m^2yr/kWh)	2.805E-04	1.903E-04	1.558E-04	1.558E-04
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	1.074E-03	7.469E-04	6.333E-04	6.333E-04

18.4.3 Social results

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	2.471E+02	2.199E+02	2.017E+02	1.886E+02
26. Total employment (person-yrs/TWh)	2.928E+02	2.606E+02	2.391E+02	2.235E+02
27. Worker injuries (injuries/TWh)	1.207E+00	7.642E-01	4.393E-01	4.393E-01
28. Human toxicity potential (kg DCB eq./kWh)	5.517E-02	3.726E-02	3.031E-02	3.031E-02
29. Health impacts from radiation (DALY/kWh)	3.234E-11	2.225E-11	1.857E-11	1.857E-11
30. Large accident fatalities (fatalities/PWh)	7.724E-01	1.155E-01	3.158E-01	3.158E-01
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	2.001E-04	2.001E-04	2.001E-04	2.001E-04
36. Diversity of fuel supply (dimensionless)	1.000E+03	1.000E+03	1.000E+03	1.000E+03
37. Fuel storage capabilities (GJ/m^3)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
38. Nuclear proliferation (ordinal scale)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
39. Depletion of elements (kg Sb eq./kWh)	6.290E-07	4.190E-07	3.339E-07	3.339E-07
40. Depletion of fossil fuels (MJ/kWh)	1.024E-01	6.976E-02	5.745E-02	5.745E-02
41. Volume of radwaste to be stored (m^3/TWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00

18.5 Solar power

18.5.1 Techno-economic results

	2020	2035	2050	2070
1. Capacity factor (%)	8.600E+00	8.600E+00	8.600E+00	8.600E+00
2. Availability factor (%)	9.590E+01	9.590E+01	9.590E+01	9.590E+01
3. Technical dispatch. (no units)	1.600E+01	1.600E+01	1.600E+01	1.600E+01
4. Economic dispatch. (no units)	9.368E+01	9.368E+01	9.368E+01	9.368E+01
5. Lifetime of fuel reserves (yrs)	1.000E+03	1.000E+03	1.000E+03	1.000E+03
6. Technological lock-in resistance (yrs^{-1})	0.000E+00	0.000E+00	0.000E+00	0.000E+00
7. Time to start-up (months)	1.000E-01	1.000E-01	1.000E-01	1.000E-01
8. Levelised cost: capital (£/MWh)	2.679E+02	1.608E+02	1.325E+02	1.156E+02
9. Levelised cost: O&M (£/MWh)	1.807E+01	1.084E+01	8.935E+00	7.792E+00
10. Levelised cost: fuel (£/MWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
11. Levelised cost: TOTAL (£/MWh)	2.860E+02	1.717E+02	1.415E+02	1.234E+02
12. Fuel price sensitivity (%)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

18.5.2 Environmental results

	2020	2035	2050	2070
14. Recyclability (ratio)	9.980E-01	9.980E-01	9.980E-01	9.980E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	1.294E-02	1.214E-02	1.094E-02	1.094E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	6.021E+01	5.533E+01	4.808E+01	4.808E+01
17. Global warming (kg CO_2 eq./kWh)	6.092E-02	5.617E-02	4.904E-02	4.904E-02
18. Ozone layer depletion (kg CFC-11 eq./kWh)	1.154E-08	1.057E-08	9.075E-09	9.075E-09
19. Acidification (kg SO_2 eq./kWh)	3.198E-04	2.997E-04	2.697E-04	2.697E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	4.840E-05	4.496E-05	3.974E-05	3.974E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	4.776E-05	4.451E-05	3.958E-05	3.958E-05
22. Land occupation (m^2yr/kWh)	3.582E-03	3.347E-03	2.991E-03	2.991E-03
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	7.292E-04	6.914E-04	6.350E-04	6.350E-04

18.5.3 Social results

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	3.085E+02	1.852E+02	1.526E+02	1.331E+02
26. Total employment (person-yrs/TWh)	3.748E+02	2.250E+02	1.854E+02	1.617E+02
27. Worker injuries (injuries/TWh)	1.561E+00	4.648E-01	1.892E-01	1.892E-01
28. Human toxicity potential (kg DCB eq./kWh)	7.404E-02	7.223E-02	6.953E-02	6.953E-02
29. Health impacts from radiation (DALY/kWh)	1.360E-09	1.252E-09	1.090E-09	1.090E-09
30. Large accident fatalities (fatalities/PWh)	1.142E+00	1.142E+00	1.142E-02	1.142E-02
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	2.001E-04	2.001E-04	2.001E-04	2.001E-04
36. Diversity of fuel supply (dimensionless)	1.000E+03	1.000E+03	1.000E+03	1.000E+03
37. Fuel storage capabilities (GJ/m^3)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
38. Nuclear proliferation (ordinal scale)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
39. Depletion of elements (kg Sb eq./kWh)	9.833E-06	9.119E-06	8.076E-06	8.076E-06
40. Depletion of fossil fuels (MJ/kWh)	7.614E-01	7.025E-01	6.140E-01	6.140E-01
41. Volume of radwaste to be stored (m^3/TWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00

18.6 Coal power with CCS

18.6.1 Techno-economic results

	2020	2035	2050	2070
1. Capacity factor (%)	6.232E+01	6.232E+01	6.232E+01	6.232E+01
2. Availability factor (%)	8.710E+01	8.710E+01	8.710E+01	8.710E+01
3. Technical dispatch. (no units)	5.000E+00	5.000E+00	5.000E+00	5.000E+00
4. Economic dispatch. (no units)	4.740E+01	5.305E+01	5.305E+01	5.305E+01
5. Lifetime of fuel reserves (yrs)	1.090E+02	9.400E+01	7.900E+01	5.900E+01
6. Technological lock-in resistance (yrs^{-1})	8.890E+00	8.890E+00	8.890E+00	8.890E+00
7. Time to start-up (months)	6.160E+01	6.160E+01	6.160E+01	6.160E+01
8. Levelised cost: capital (£/MWh)	4.645E+01	5.591E+01	5.365E+01	5.202E+01
9. Levelised cost: O&M (£/MWh)	1.670E+01	2.631E+01	2.525E+01	2.448E+01
10. Levelised cost: fuel (£/MWh)	2.740E+01	2.318E+01	2.224E+01	2.156E+01
11. Levelised cost: TOTAL (£/MWh)	9.800E+01	1.054E+02	1.011E+02	9.806E+01
12. Fuel price sensitivity (%)	2.796E+01	2.199E+01	2.199E+01	2.199E+01
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

18.6.2 Environmental results

	2020	2035	2050	2070
14. Recyclability (ratio)	8.430E-01	8.430E-01	8.430E-01	8.430E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	1.674E-02	1.378E-02	1.275E-02	1.087E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	5.655E+02	4.735E+02	4.443E+02	4.023E+02
17. Global warming (kg CO_2 eq./kWh)	2.694E-01	1.730E-01	1.603E-01	8.803E-02
18. Ozone layer depletion (kg CFC-11 eq./kWh)	6.214E-09	4.612E-09	4.376E-09	3.595E-09
19. Acidification (kg SO_2 eq./kWh)	1.449E-03	1.026E-03	9.847E-04	6.552E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	2.650E-05	1.725E-05	1.658E-05	9.218E-06
21. Photochemical smog (kg C_2H_4 eq./kWh)	1.103E-04	8.695E-05	8.219E-05	6.878E-05
22. Land occupation (m^2yr/kWh)	3.095E-02	2.603E-02	2.406E-02	2.127E-02
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	2.409E-03	2.000E-03	1.841E-03	1.569E-03

18.6.3 Social results

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	5.645E+01	4.749E+01	4.542E+01	4.404E+01
26. Total employment (person-yrs/TWh)	2.142E+02	1.786E+02	1.708E+02	1.656E+02
27. Worker injuries (injuries/TWh)	2.484E+00	9.500E-01	4.254E-01	4.254E-01
28. Human toxicity potential (kg DCB eq./kWh)	1.498E-01	1.039E-01	9.780E-02	6.543E-02
29. Health impacts from radiation (DALY/kWh)	9.754E-10	3.858E-10	5.824E-10	4.072E-10
30. Large accident fatalities (fatalities/PWh)	2.056E+01	2.056E+01	1.569E+01	1.569E+01
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a

32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	n/a	n/a	n/a	n/a
36. Diversity of fuel supply (dimensionless)	7.064E+01	7.064E+01	7.064E+01	7.064E+01
37. Fuel storage capabilities (GJ/m^3)	2.117E+01	2.117E+01	2.117E+01	2.117E+01
38. Nuclear proliferation (ordinal scale)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
39. Depletion of elements (kg Sb eq./kWh)	3.284E-07	2.524E-07	2.318E-07	1.756E-07
40. Depletion of fossil fuels (MJ/kWh)	1.474E+01	1.229E+01	1.156E+01	1.042E+01
41. Volume of radwaste to be stored (m^3/TWh)	0.000E+00	0.000E+00	0.000E+00	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	7.484E-01	7.484E-01	7.484E-01	7.484E-01

19 Appendix 8: Future electricity mix scenario results

19.1 Sub-scenario 65%-1

19.1.1 Techno-economic results (per year)

	2020	2035	2050	2070
1. Capacity factor (%)	6.270E+01	6.043E+01	5.905E+01	5.504E+01
2. Availability factor (%)	8.855E+01	8.887E+01	8.924E+01	8.988E+01
3. Technical dispatch. (no units)	7.799E+00	8.102E+00	8.398E+00	8.886E+00
4. Economic dispatch. (no units)	3.543E+01	3.775E+01	4.619E+01	5.744E+01
5. Lifetime of fuel reserves (yrs)	1.192E+02	1.739E+02	2.419E+02	3.539E+02
6. Technological lock-in resistance (yrs^{-1})	1.171E+01	1.118E+01	9.317E+00	6.827E+00
7. Time to start-up (months)	4.476E+01	4.248E+01	4.350E+01	4.221E+01
8. Levelised cost: capital (£)	8.930E+09	1.300E+10	1.917E+10	2.723E+10
9. Levelised cost: O&M (£)	3.052E+09	4.867E+09	7.465E+09	9.883E+09
10. Levelised cost: fuel (£)	1.158E+10	1.242E+10	1.093E+10	8.133E+09
11. Levelised cost: TOTAL (£)	2.355E+10	3.027E+10	3.755E+10	4.524E+10
12. Fuel price sensitivity (%)	5.176E+01	4.744E+01	3.521E+01	2.099E+01
13. Financial incentives (£)	n/a	n/a	n/a	n/a

19.1.2 Environmental results (per year)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.751E-01	8.848E-01	8.886E-01	8.971E-01
15. Freshwater eco-toxicity (kg DCB eq.)	3.158E+09	3.267E+09	3.666E+09	4.352E+09
16. Marine eco-toxicity (kg DCB eq.)	6.723E+13	7.542E+13	8.685E+13	1.102E+14
17. Global warming (kg CO_2 eq.)	1.883E+11	1.660E+11	9.624E+10	5.312E+10
18. Ozone layer depletion (kg CFC-11 eq.)	2.827E+03	3.056E+03	2.637E+03	1.932E+03
19. Acidification (kg SO_2 eq.)	2.272E+08	2.303E+08	2.195E+08	2.013E+08
20. Eutrophication (kg PO_4^{3-} eq.)	3.626E+07	3.116E+07	1.687E+07	1.140E+07
21. Photochemical smog (kg C_2H_4 eq.)	2.088E+07	2.163E+07	2.046E+07	2.170E+07
22. Land occupation (m^2yr)	3.177E+09	3.785E+09	4.604E+09	5.734E+09
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq.)	2.357E+08	3.035E+08	4.117E+08	5.073E+08

19.1.3 Social results (per year)

	2020	2035	2050	2070
25. Direct employment (person-yrs)	1.680E+04	2.222E+04	2.826E+04	3.834E+04
26. Total employment (person-yrs)	3.985E+04	4.908E+04	5.942E+04	7.669E+04
27. Worker injuries (injuries)	3.226E+02	1.914E+02	1.212E+02	1.691E+02
28. Human toxicity potential (kg DCB eq.)	1.371E+10	1.599E+10	2.229E+10	2.322E+10
29. Health impacts from radiation (DALY)	6.847E+02	3.167E+02	3.383E+02	1.635E+02
30. Large accident fatalities (fatalities)	3.231E+00	2.765E+00	3.924E+00	4.485E+00
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe)	8.765E+06	1.081E+07	1.793E+07	2.917E+07
36. Diversity of fuel supply (dimensionless)	8.201E+01	8.256E+01	8.212E+01	8.184E+01
37. Fuel storage capabilities (GJ/m^3)	8.417E+05	2.436E+05	2.250E+05	1.207E+01
38. Nuclear proliferation (ordinal scale)	2.679E+00	7.754E-01	7.162E-01	0.000E+00
39. Depletion of elements (kg Sb eq.)	5.547E+04	1.121E+05	1.662E+05	3.771E+05
40. Depletion of fossil fuels (MJ)	2.732E+12	2.974E+12	2.965E+12	3.067E+12
41. Volume of radwaste to be stored (m^3)	2.774E+02	8.985E+01	8.987E+01	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3)	0.000E+00	4.227E+07	1.251E+08	1.875E+08

19.1.4 Techno-economic results (per unit of electricity generated)

	2020	2035	2050	2070
1. Capacity factor (%)	6.270E+01	6.043E+01	5.905E+01	5.504E+01
2. Availability factor (%)	8.855E+01	8.887E+01	8.924E+01	8.988E+01
3. Technical dispatch. (no units)	7.799E+00	8.102E+00	8.398E+00	8.886E+00
4. Economic dispatch. (no units)	3.543E+01	3.775E+01	4.619E+01	5.744E+01
5. Lifetime of fuel reserves (yrs)	1.192E+02	1.739E+02	2.419E+02	3.539E+02
6. Technological lock-in resistance (yrs^{-1})	1.171E+01	1.118E+01	9.317E+00	6.827E+00
7. Time to start-up (months)	4.476E+01	4.248E+01	4.350E+01	4.221E+01
8. Levelised cost: capital (£/MWh)	2.654E+01	3.451E+01	4.701E+01	5.977E+01
9. Levelised cost: O&M (£/MWh)	9.071E+00	1.293E+01	1.831E+01	2.170E+01
10. Levelised cost: fuel (£/MWh)	3.443E+01	3.299E+01	2.682E+01	1.785E+01
11. Levelised cost: TOTAL (£/MWh)	6.998E+01	8.038E+01	9.210E+01	9.931E+01
12. Fuel price sensitivity (%)	5.176E+01	4.744E+01	3.521E+01	2.099E+01
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

19.1.5 Environmental results (per unit of electricity generated)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.751E-01	8.848E-01	8.886E-01	8.971E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	9.386E-03	8.677E-03	8.991E-03	9.553E-03
16. Marine eco-toxicity (kg DCB eq./kWh)	1.998E+02	2.003E+02	2.130E+02	2.418E+02
17. Global warming (kg CO_2 eq./kWh)	5.598E-01	4.409E-01	2.360E-01	1.166E-01

18. Ozone layer depletion (kg CFC-11 eq./kWh)	8.403E-09	8.117E-09	6.467E-09	4.242E-09
19. Acidification (kg SO_2 eq./kWh)	6.752E-04	6.116E-04	5.383E-04	4.418E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	1.078E-04	8.275E-05	4.137E-05	2.503E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	6.207E-05	5.744E-05	5.019E-05	4.763E-05
22. Land occupation (m^2yr/kWh)	9.442E-03	1.005E-02	1.129E-02	1.259E-02
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	7.005E-04	8.060E-04	1.010E-03	1.114E-03

19.1.6 Social results (per unit of electricity generated)

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	4.992E+01	5.901E+01	6.932E+01	8.417E+01
26. Total employment (person-yrs/TWh)	1.184E+02	1.303E+02	1.457E+02	1.683E+02
27. Worker injuries (injuries/TWh)	9.588E-01	5.082E-01	2.974E-01	3.713E-01
28. Human toxicity potential (kg DCB eq./kWh)	4.076E-02	4.246E-02	5.467E-02	5.097E-02
29. Health impacts from radiation (DALY/kWh)	2.035E-09	8.410E-10	8.297E-10	3.588E-10
30. Large accident fatalities (fatalities/PWh)	9.604E+00	7.343E+00	9.624E+00	9.845E+00
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	2.605E-05	2.871E-05	4.396E-05	6.403E-05
36. Diversity of fuel supply (dimensionless)	8.201E+01	8.256E+01	8.212E+01	8.184E+01
37. Fuel storage capabilities (GJ/m^3)	8.417E+05	2.436E+05	2.250E+05	1.207E+01
38. Nuclear proliferation (ordinal scale)	2.679E+00	7.754E-01	7.162E-01	0.000E+00
39. Depletion of elements (kg Sb eq./kWh)	1.649E-07	2.977E-07	4.077E-07	8.278E-07
40. Depletion of fossil fuels (MJ/kWh)	8.120E+00	7.899E+00	7.271E+00	6.732E+00
41. Volume of radwaste to be stored (m^3/TWh)	8.246E-01	2.386E-01	2.204E-01	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	0.000E+00	1.123E-01	3.069E-01	4.116E-01

19.2 Sub-scenario 65%-2

19.2.1 Techno-economic results (per year)

	2020	2035	2050	2070
1. Capacity factor (%)	6.391E+01	6.481E+01	6.570E+01	6.224E+01
2. Availability factor (%)	8.844E+01	8.869E+01	8.922E+01	9.033E+01
3. Technical dispatch. (no units)	7.803E+00	8.163E+00	8.974E+00	1.038E+01
4. Economic dispatch. (no units)	3.630E+01	4.400E+01	5.455E+01	6.218E+01
5. Lifetime of fuel reserves (yrs)	1.059E+02	1.328E+02	1.885E+02	3.108E+02
6. Technological lock-in resistance (yrs^{-1})	1.149E+01	9.703E+00	7.178E+00	5.214E+00
7. Time to start-up (months)	4.604E+01	4.802E+01	4.974E+01	4.457E+01
8. Levelised cost: capital (£)	8.705E+09	1.326E+10	1.913E+10	2.574E+10
9. Levelised cost: O&M (£)	2.992E+09	4.438E+09	6.136E+09	7.509E+09
10. Levelised cost: fuel (£)	1.137E+10	1.062E+10	8.339E+09	6.712E+09

11. Levelised cost: TOTAL (£)	2.304E+10	2.831E+10	3.360E+10	3.995E+10
12. Fuel price sensitivity (%)	5.081E+01	4.113E+01	2.815E+01	1.970E+01
13. Financial incentives (£)	n/a	n/a	n/a	n/a

19.2.2 Environmental results (per year)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.708E-01	8.682E-01	8.675E-01	8.851E-01
15. Freshwater eco-toxicity (kg DCB eq.)	3.269E+09	4.230E+09	5.191E+09	5.682E+09
16. Marine eco-toxicity (kg DCB eq.)	6.550E+13	7.690E+13	7.492E+13	6.033E+13
17. Global warming (kg CO_2 eq.)	1.831E+11	1.644E+11	1.039E+11	5.734E+10
18. Ozone layer depletion (kg CFC-11 eq.)	2.750E+03	2.551E+03	1.973E+03	1.732E+03
19. Acidification (kg SO_2 eq.)	2.203E+08	2.335E+08	1.991E+08	1.272E+08
20. Eutrophication (kg PO_4^{3-} eq.)	3.521E+07	3.191E+07	2.096E+07	1.459E+07
21. Photochemical smog (kg C_2H_4 eq.)	2.026E+07	2.120E+07	1.801E+07	1.376E+07
22. Land occupation (m^2yr)	3.081E+09	3.706E+09	3.661E+09	2.871E+09
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq.)	2.340E+08	3.144E+08	3.784E+08	3.808E+08

19.2.3 Social results (per year)

	2020	2035	2050	2070
25. Direct employment (person-yrs)	1.591E+04	2.080E+04	2.711E+04	3.771E+04
26. Total employment (person-yrs)	3.841E+04	4.665E+04	5.339E+04	6.259E+04
27. Worker injuries (injuries)	3.119E+02	1.825E+02	1.038E+02	1.204E+02
28. Human toxicity potential (kg DCB eq.)	1.451E+10	2.114E+10	2.868E+10	2.950E+10
29. Health impacts from radiation (DALY)	9.204E+02	1.515E+03	2.479E+03	2.891E+03
30. Large accident fatalities (fatalities)	3.135E+00	2.414E+00	2.831E+00	2.390E+00
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe)	1.020E+07	1.935E+07	3.507E+07	5.377E+07
36. Diversity of fuel supply (dimensionless)	8.184E+01	8.167E+01	8.244E+01	8.559E+01
37. Fuel storage capabilities (GJ/m^3)	1.209E+06	1.884E+06	2.952E+06	3.120E+06
38. Nuclear proliferation (ordinal scale)	3.849E+00	5.997E+00	9.398E+00	9.932E+00
39. Depletion of elements (kg Sb eq.)	4.022E+04	8.708E+04	1.482E+05	3.539E+05
40. Depletion of fossil fuels (MJ)	2.656E+12	2.751E+12	2.337E+12	1.752E+12
41. Volume of radwaste to be stored (m^3)	3.983E+02	6.951E+02	1.179E+03	1.392E+03
42. Volume of liquid CO_2 to be stored (m^3)	0.000E+00	2.819E+07	6.714E+07	7.500E+07

19.2.4 Techno-economic results (per unit of electricity generated)

	2020	2035	2050	2070
1. Capacity factor (%)	6.391E+01	6.481E+01	6.570E+01	6.224E+01
2. Availability factor (%)	8.844E+01	8.869E+01	8.922E+01	9.033E+01
3. Technical dispatch. (no units)	7.803E+00	8.163E+00	8.974E+00	1.038E+01
4. Economic dispatch. (no units)	3.630E+01	4.400E+01	5.455E+01	6.218E+01
5. Lifetime of fuel reserves (yrs)	1.059E+02	1.328E+02	1.885E+02	3.108E+02
6. Technological lock-in resistance (yrs^{-1})	1.149E+01	9.703E+00	7.178E+00	5.214E+00
7. Time to start-up (months)	4.604E+01	4.802E+01	4.974E+01	4.457E+01
8. Levelised cost: capital (£/MWh)	2.589E+01	3.522E+01	4.692E+01	5.651E+01
9. Levelised cost: O&M (£/MWh)	8.897E+00	1.178E+01	1.505E+01	1.648E+01
10. Levelised cost: fuel (£/MWh)	3.380E+01	2.820E+01	2.045E+01	1.473E+01
11. Levelised cost: TOTAL (£/MWh)	6.853E+01	7.516E+01	8.239E+01	8.771E+01
12. Fuel price sensitivity (%)	5.081E+01	4.113E+01	2.815E+01	1.970E+01
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

19.2.5 Environmental results (per unit of electricity generated)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.708E-01	8.682E-01	8.675E-01	8.850E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	9.721E-03	1.123E-02	1.273E-02	1.247E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	1.948E+02	2.042E+02	1.837E+02	1.324E+02
17. Global warming (kg CO_2 eq./kWh)	5.444E-01	4.366E-01	2.549E-01	1.259E-01
18. Ozone layer depletion (kg CFC-11 eq./kWh)	8.177E-09	6.773E-09	4.839E-09	3.802E-09
19. Acidification (kg SO_2 eq./kWh)	6.553E-04	6.199E-04	4.884E-04	2.792E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	1.047E-04	8.472E-05	5.139E-05	3.203E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	6.026E-05	5.628E-05	4.417E-05	3.022E-05
22. Land occupation (m^2yr/kWh)	9.163E-03	9.840E-03	8.979E-03	6.303E-03
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	6.958E-04	8.348E-04	9.279E-04	8.360E-04

19.2.6 Social results (per unit of electricity generated)

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	4.732E+01	5.524E+01	6.648E+01	8.279E+01
26. Total employment (person-yrs/TWh)	1.142E+02	1.239E+02	1.309E+02	1.374E+02
27. Worker injuries (injuries/TWh)	9.277E-01	4.847E-01	2.546E-01	2.643E-01
28. Human toxicity potential (kg DCB eq./kWh)	4.314E-02	5.612E-02	7.034E-02	6.475E-02
29. Health impacts from radiation (DALY/kWh)	2.737E-09	4.022E-09	6.078E-09	6.346E-09
30. Large accident fatalities (fatalities/PWh)	9.324E+00	6.411E+00	6.943E+00	5.246E+00
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	3.034E-05	5.137E-05	8.600E-05	1.181E-04

36. Diversity of fuel supply (dimensionless)	8.184E+01	8.167E+01	8.244E+01	8.559E+01
37. Fuel storage capabilities (GJ/m^3)	1.209E+06	1.884E+06	2.952E+06	3.120E+06
38. Nuclear proliferation (ordinal scale)	3.849E+00	5.997E+00	9.398E+00	9.932E+00
39. Depletion of elements (kg Sb eq./kWh)	1.196E-07	2.312E-07	3.634E-07	7.769E-07
40. Depletion of fossil fuels (MJ/kWh)	7.899E+00	7.304E+00	5.730E+00	3.847E+00
41. Volume of radwaste to be stored (m^3/TWh)	1.185E+00	1.846E+00	2.892E+00	3.057E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	0.000E+00	7.484E-02	1.647E-01	1.647E-01

19.3 Sub-scenario 80%

19.3.1 Techno-economic results (per year)

	2020	**2035**	**2050**	**2070**
1. Capacity factor (%)	6.201E+01	6.440E+01	6.091E+01	5.608E+01
2. Availability factor (%)	8.907E+01	8.980E+01	9.122E+01	9.224E+01
3. Technical dispatch. (no units)	8.592E+00	9.803E+00	1.172E+01	1.285E+01
4. Economic dispatch. (no units)	3.754E+01	5.283E+01	6.695E+01	7.623E+01
5. Lifetime of fuel reserves (yrs)	1.667E+02	2.571E+02	4.274E+02	5.417E+02
6. Technological lock-in resistance (yrs^{-1})	1.104E+01	7.250E+00	3.732E+00	1.655E+00
7. Time to start-up (months)	4.260E+01	4.459E+01	3.984E+01	3.561E+01
8. Levelised cost: capital (£)	1.111E+10	1.850E+10	3.500E+10	3.597E+10
9. Levelised cost: O&M (£)	3.559E+09	5.590E+09	9.240E+09	8.508E+09
10. Levelised cost: fuel (£)	1.165E+10	8.206E+09	5.824E+09	2.170E+09
11. Levelised cost: TOTAL (£)	2.630E+10	3.228E+10	5.006E+10	4.665E+10
12. Fuel price sensitivity (%)	4.946E+01	3.099E+01	1.511E+01	5.551E+00
13. Financial incentives (£)	n/a	n/a	n/a	n/a

19.3.2 Environmental results (per year)

	2020	**2035**	**2050**	**2070**
14. Recyclability (ratio)	8.829E-01	8.814E-01	8.989E-01	9.130E-01
15. Freshwater eco-toxicity (kg DCB eq.)	3.311E+09	4.674E+09	7.008E+09	6.651E+09
16. Marine eco-toxicity (kg DCB eq.)	5.325E+13	5.405E+13	4.939E+13	3.578E+13
17. Global warming (kg CO_2 eq.)	1.643E+11	1.107E+11	6.035E+10	1.196E+10
18. Ozone layer depletion (kg CFC-11 eq.)	2.883E+03	2.035E+03	1.762E+03	1.192E+03
19. Acidification (kg SO_2 eq.)	1.840E+08	1.589E+08	1.280E+08	7.312E+07
20. Eutrophication (kg PO_4^{3-} eq.)	3.231E+07	2.365E+07	1.778E+07	1.043E+07
21. Photochemical smog (kg C_2H_4 eq.)	1.773E+07	1.498E+07	1.272E+07	8.791E+06
22. Land occupation (m^2yr)	2.480E+09	2.510E+09	2.196E+09	1.529E+09
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq.)	2.266E+08	2.999E+08	4.114E+08	3.738E+08

19.3.3 Social results (per year)

	2020	2035	2050	2070
25. Direct employment (person-yrs)	2.137E+04	3.062E+04	5.601E+04	5.515E+04
26. Total employment (person-yrs)	4.247E+04	5.216E+04	8.019E+04	7.436E+04
27. Worker injuries (injuries)	2.976E+02	1.782E+02	1.388E+02	1.321E+02
28. Human toxicity potential (kg DCB eq.)	1.424E+10	2.319E+10	3.667E+10	3.469E+10
29. Health impacts from radiation (DALY)	9.136E+02	2.149E+03	3.805E+03	3.629E+03
30. Large accident fatalities (fatalities)	2.754E+00	1.719E+00	1.688E+00	9.072E-01
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe)	1.519E+07	3.638E+07	7.916E+07	8.573E+07
36. Diversity of fuel supply (dimensionless)	8.412E+01	8.521E+01	8.884E+01	9.101E+01
37. Fuel storage capabilities (GJ/m^3)	1.154E+06	2.734E+06	3.520E+06	3.705E+06
38. Nuclear proliferation (ordinal scale)	3.675E+00	8.702E+00	1.121E+01	1.179E+01
39. Depletion of elements (kg Sb eq.)	8.399E+04	1.552E+05	5.105E+05	8.147E+05
40. Depletion of fossil fuels (MJ)	2.396E+12	1.909E+12	1.368E+12	6.486E+11
41. Volume of radwaste to be stored (m^3)	3.986E+02	1.028E+03	1.845E+03	1.756E+03
42. Volume of liquid CO_2 to be stored (m^3)	0.000E+00	2.298E+07	4.003E+07	3.984E+07

19.3.4 Techno-economic results (per unit of electricity generated)

	2020	2035	2050	2070
1. Capacity factor (%)	6.201E+01	6.440E+01	6.091E+01	5.608E+01
2. Availability factor (%)	8.907E+01	8.980E+01	9.122E+01	9.224E+01
3. Technical dispatch. (no units)	8.592E+00	9.803E+00	1.172E+01	1.285E+01
4. Economic dispatch. (no units)	3.754E+01	5.283E+01	6.695E+01	7.623E+01
5. Lifetime of fuel reserves (yrs)	1.667E+02	2.571E+02	4.274E+02	5.417E+02
6. Technological lock-in resistance (yrs^{-1})	1.104E+01	7.250E+00	3.732E+00	1.655E+00
7. Time to start-up (months)	4.260E+01	4.459E+01	3.984E+01	3.561E+01
8. Levelised cost: capital (£/MWh)	3.152E+01	4.819E+01	6.544E+01	7.434E+01
9. Levelised cost: O&M (£/MWh)	1.010E+01	1.456E+01	1.727E+01	1.758E+01
10. Levelised cost: fuel (£/MWh)	3.306E+01	2.138E+01	1.089E+01	4.485E+00
11. Levelised cost: TOTAL (£/MWh)	7.462E+01	8.411E+01	9.359E+01	9.641E+01
12. Fuel price sensitivity (%)	4.946E+01	3.099E+01	1.511E+01	5.551E+00
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

19.3.5 Environmental results (per unit of electricity generated)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.828E-01	8.814E-01	8.988E-01	9.128E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	9.394E-03	1.218E-02	1.310E-02	1.375E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	1.511E+02	1.408E+02	9.233E+01	7.395E+01
17. Global warming (kg CO_2 eq./kWh)	4.661E-01	2.884E-01	1.128E-01	2.472E-02

18. Ozone layer depletion (kg CFC-11 eq./kWh)	8.180E-09	5.301E-09	3.294E-09	2.463E-09
19. Acidification (kg SO_2 eq./kWh)	5.220E-04	4.140E-04	2.393E-04	1.511E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	9.166E-05	6.161E-05	3.324E-05	2.155E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	5.030E-05	3.902E-05	2.378E-05	1.817E-05
22. Land occupation (m^2yr/kWh)	7.036E-03	6.539E-03	4.106E-03	3.159E-03
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	6.430E-04	7.814E-04	7.691E-04	7.725E-04

19.3.6 Social results (per unit of electricity generated)

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	6.064E+01	7.978E+01	1.047E+02	1.140E+02
26. Total employment (person-yrs/TWh)	1.205E+02	1.359E+02	1.499E+02	1.537E+02
27. Worker injuries (injuries/TWh)	8.444E-01	4.643E-01	2.595E-01	2.730E-01
28. Human toxicity potential (kg DCB eq./kWh)	4.039E-02	6.042E-02	6.856E-02	7.169E-02
29. Health impacts from radiation (DALY/kWh)	2.592E-09	5.598E-09	7.113E-09	7.500E-09
30. Large accident fatalities (fatalities/PWh)	7.814E+00	4.479E+00	3.156E+00	1.875E+00
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	4.309E-05	9.479E-05	1.480E-04	1.772E-04
36. Diversity of fuel supply (dimensionless)	8.412E+01	8.521E+01	8.884E+01	9.101E+01
37. Fuel storage capabilities (GJ/m^3)	1.154E+06	2.734E+06	3.520E+06	3.705E+06
38. Nuclear proliferation (ordinal scale)	3.675E+00	8.702E+00	1.121E+01	1.179E+01
39. Depletion of elements (kg Sb eq./kWh)	2.383E-07	4.044E-07	9.543E-07	1.684E-06
40. Depletion of fossil fuels (MJ/kWh)	6.797E+00	4.974E+00	2.557E+00	1.340E+00
41. Volume of radwaste to be stored (m^3/TWh)	1.131E+00	2.678E+00	3.449E+00	3.630E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	0.000E+00	5.987E-02	7.484E-02	8.233E-02

19.4 Sub-scenario 100%-1

19.4.1 Techno-economic results (per year)

	2020	2035	2050	2070
1. Capacity factor (%)	6.057E+01	4.588E+01	2.883E+01	2.734E+01
2. Availability factor (%)	8.651E+01	9.260E+01	9.530E+01	9.548E+01
3. Technical dispatch. (no units)	8.504E+00	1.255E+01	1.586E+01	1.598E+01
4. Economic dispatch. (no units)	3.634E+01	6.849E+01	8.467E+01	8.514E+01
5. Lifetime of fuel reserves (yrs)	1.905E+02	6.742E+02	9.800E+02	9.981E+02
6. Technological lock-in resistance (yrs^{-1})	1.065E+01	3.612E+00	6.319E-02	1.778E-02
7. Time to start-up (months)	3.954E+01	2.525E+01	7.222E+00	5.938E+00
8. Levelised cost: capital (£)	1.127E+10	3.549E+10	5.953E+10	4.889E+10
9. Levelised cost: O&M (£)	3.661E+09	9.034E+09	9.938E+09	8.197E+09
10. Levelised cost: fuel (£)	1.124E+10	3.941E+09	9.359E+07	2.086E+07

11. Levelised cost: TOTAL (£)	2.615E+10	4.846E+10	6.956E+10	5.711E+10
12. Fuel price sensitivity (%)	4.775E+01	1.220E+01	2.156E-01	4.398E-02
13. Financial incentives (£)	n/a	n/a	n/a	n/a

19.4.2 Environmental results (per year)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.867E-01	9.454E-01	9.920E-01	9.959E-01
15. Freshwater eco-toxicity (kg DCB eq.)	3.320E+09	4.336E+09	5.394E+09	4.799E+09
16. Marine eco-toxicity (kg DCB eq.)	5.697E+13	5.265E+13	1.926E+13	1.711E+13
17. Global warming (kg CO_2 eq.)	1.612E+11	3.472E+10	1.534E+10	1.411E+10
18. Ozone layer depletion (kg CFC-11 eq.)	2.863E+03	1.798E+03	2.629E+03	2.464E+03
19. Acidification (kg SO_2 eq.)	1.922E+08	1.319E+08	8.650E+07	7.942E+07
20. Eutrophication (kg PO_4^{3-} eq.)	3.176E+07	1.253E+07	1.703E+07	1.566E+07
21. Photochemical smog (kg C_2H_4 eq.)	1.825E+07	1.342E+07	1.220E+07	1.131E+07
22. Land occupation (m^2yr)	2.701E+09	2.736E+09	9.357E+08	8.473E+08
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq.)	2.474E+08	3.772E+08	3.426E+08	3.077E+08

19.4.3 Social results (per year)

	2020	2035	2050	2070
25. Direct employment (person-yrs)	2.338E+04	5.752E+04	9.240E+04	7.636E+04
26. Total employment (person-yrs)	4.562E+04	8.109E+04	1.112E+05	9.165E+04
27. Worker injuries (injuries)	3.222E+02	2.588E+02	1.616E+02	1.462E+02
28. Human toxicity potential (kg DCB eq.)	1.468E+10	2.295E+10	2.813E+10	2.509E+10
29. Health impacts from radiation (DALY)	6.781E+02	3.320E+02	4.918E+02	2.935E+02
30. Large accident fatalities (fatalities)	2.877E+00	2.131E+00	1.133E-01	8.695E-02
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe)	1.476E+07	5.148E+07	1.066E+08	9.659E+07
36. Diversity of fuel supply (dimensionless)	8.419E+01	9.142E+01	9.957E+01	9.994E+01
37. Fuel storage capabilities (GJ/m^3)	8.036E+05	2.390E+05	1.715E+05	4.233E-02
38. Nuclear proliferation (ordinal scale)	2.558E+00	7.608E-01	5.459E-01	0.000E+00
39. Depletion of elements (kg Sb eq.)	9.254E+04	8.536E+05	2.354E+06	2.213E+06
40. Depletion of fossil fuels (MJ)	2.466E+12	1.402E+12	2.121E+11	1.853E+11
41. Volume of radwaste to be stored (m^3)	2.772E+02	8.990E+01	8.986E+01	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3)	7.907E+06	6.897E+07	1.601E+06	7.240E+05

19.4.4 Techno-economic results (per unit of electricity generated)

	2020	2035	2050	2070
1. Capacity factor (%)	6.057E+01	4.588E+01	2.883E+01	2.734E+01
2. Availability factor (%)	8.651E+01	9.260E+01	9.530E+01	9.548E+01
3. Technical dispatch. (no units)	8.504E+00	1.255E+01	1.586E+01	1.598E+01
4. Economic dispatch. (no units)	3.634E+01	6.849E+01	8.467E+01	8.514E+01
5. Lifetime of fuel reserves (yrs)	1.905E+02	6.742E+02	9.800E+02	9.981E+02
6. Technological lock-in resistance (yrs^{-1})	1.065E+01	3.612E+00	6.319E-02	1.778E-02
7. Time to start-up (months)	3.954E+01	2.525E+01	7.222E+00	5.938E+00
8. Levelised cost: capital (£/MWh)	3.200E+01	9.244E+01	1.113E+02	1.011E+02
9. Levelised cost: O&M (£/MWh)	1.040E+01	2.353E+01	1.858E+01	1.695E+01
10. Levelised cost: fuel (£/MWh)	3.192E+01	1.026E+01	1.750E-01	4.313E-02
11. Levelised cost: TOTAL (£/MWh)	7.427E+01	1.262E+02	1.301E+02	1.181E+02
12. Fuel price sensitivity (%)	4.775E+01	1.220E+01	2.156E-01	4.398E-02
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

19.4.5 Environmental results (per unit of electricity generated)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.867E-01	9.452E-01	9.915E-01	9.953E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	9.428E-03	1.129E-02	1.009E-02	9.922E-03
16. Marine eco-toxicity (kg DCB eq./kWh)	1.618E+02	1.371E+02	3.600E+01	3.537E+01
17. Global warming (kg CO_2 eq./kWh)	4.578E-01	9.043E-02	2.868E-02	2.917E-02
18. Ozone layer depletion (kg CFC-11 eq./kWh)	8.128E-09	4.683E-09	4.915E-09	5.095E-09
19. Acidification (kg SO_2 eq./kWh)	5.458E-04	3.435E-04	1.617E-04	1.642E-04
20. Eutrophication (kg PO_4^{3-} eq./kWh)	9.019E-05	3.263E-05	3.183E-05	3.237E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	5.181E-05	3.494E-05	2.280E-05	2.339E-05
22. Land occupation (m^2yr/kWh)	7.671E-03	7.125E-03	1.749E-03	1.752E-03
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	7.026E-04	9.825E-04	6.405E-04	6.361E-04

19.4.6 Social results (per unit of electricity generated)

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	6.640E+01	1.498E+02	1.728E+02	1.579E+02
26. Total employment (person-yrs/TWh)	1.295E+02	2.112E+02	2.078E+02	1.895E+02
27. Worker injuries (injuries/TWh)	9.150E-01	6.740E-01	3.021E-01	3.022E-01
28. Human toxicity potential (kg DCB eq./kWh)	4.169E-02	5.976E-02	5.259E-02	5.187E-02
29. Health impacts from radiation (DALY/kWh)	1.926E-09	8.648E-10	9.194E-10	6.067E-10
30. Large accident fatalities (fatalities/PWh)	8.169E+00	5.551E+00	2.119E-01	1.798E-01
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	4.192E-05	1.341E-04	1.992E-04	1.997E-04

36. Diversity of fuel supply (dimensionless)	8.419E+01	9.142E+01	9.957E+01	9.994E+01
37. Fuel storage capabilities (GJ/m^3)	8.036E+05	2.390E+05	1.715E+05	4.233E-02
38. Nuclear proliferation (ordinal scale)	2.558E+00	7.608E-01	5.459E-01	0.000E+00
39. Depletion of elements (kg Sb eq./kWh)	2.628E-07	2.223E-06	4.401E-06	4.576E-06
40. Depletion of fossil fuels (MJ/kWh)	7.002E+00	3.651E+00	3.965E-01	3.832E-01
41. Volume of radwaste to be stored (m^3/TWh)	7.872E-01	2.341E-01	1.680E-01	0.000E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	2.245E-02	1.796E-01	2.994E-03	1.497E-03

19.5 Sub-scenario 100%-2

19.5.1 Techno-economic results (per year)

	2020	2035	2050	2070
1. Capacity factor (%)	6.289E+01	6.402E+01	6.005E+01	5.967E+01
2. Availability factor (%)	8.640E+01	9.117E+01	9.240E+01	9.222E+01
3. Technical dispatch. (no units)	8.415E+00	1.188E+01	1.346E+01	1.330E+01
4. Economic dispatch. (no units)	3.844E+01	6.752E+01	7.829E+01	7.900E+01
5. Lifetime of fuel reserves (yrs)	1.604E+02	4.046E+02	5.461E+02	5.071E+02
6. Technological lock-in resistance (yrs^{-1})	1.022E+01	3.494E+00	8.189E-01	8.539E-01
7. Time to start-up (months)	4.244E+01	4.214E+01	3.692E+01	3.812E+01
8. Levelised cost: capital (£)	1.125E+10	2.630E+10	4.180E+10	3.550E+10
9. Levelised cost: O&M (£)	3.493E+09	6.840E+09	9.507E+09	7.544E+09
10. Levelised cost: fuel (£)	1.076E+10	4.092E+09	1.353E+09	1.280E+09
11. Levelised cost: TOTAL (£)	2.549E+10	3.722E+10	5.266E+10	4.433E+10
12. Fuel price sensitivity (%)	4.572E+01	1.475E+01	3.707E+00	3.907E+00
13. Financial incentives (£)	n/a	n/a	n/a	n/a

19.5.2 Environmental results (per year)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.785E-01	8.924E-01	9.087E-01	9.030E-01
15. Freshwater eco-toxicity (kg DCB eq.)	3.607E+09	5.522E+09	7.948E+09	7.401E+09
16. Marine eco-toxicity (kg DCB eq.)	5.747E+13	2.563E+13	1.866E+13	1.724E+13
17. Global warming (kg CO_2 eq.)	1.569E+11	2.758E+10	6.918E+09	6.802E+09
18. Ozone layer depletion (kg CFC-11 eq.)	2.721E+03	1.215E+03	9.487E+02	1.006E+03
19. Acidification (kg SO_2 eq.)	1.909E+08	5.974E+07	4.219E+07	4.103E+07
20. Eutrophication (kg PO_4^{3-} eq.)	3.083E+07	1.046E+07	1.133E+07	1.035E+07
21. Photochemical smog (kg C_2H_4 eq.)	1.798E+07	6.661E+06	5.395E+06	5.419E+06
22. Land occupation (m^2yr)	2.705E+09	1.042E+09	4.684E+08	4.513E+08
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq.)	2.509E+08	2.930E+08	3.685E+08	3.330E+08

19.5.3 Social results (per year)

	2020	2035	2050	2070
25. Direct employment (person-yrs)	2.154E+04	4.192E+04	6.694E+04	5.379E+04
26. Total employment (person-yrs)	4.342E+04	5.749E+04	8.362E+04	6.775E+04
27. Worker injuries (injuries)	3.132E+02	1.665E+02	1.332E+02	1.111E+02
28. Human toxicity potential (kg DCB eq.)	1.672E+10	2.834E+10	4.082E+10	3.873E+10
29. Health impacts from radiation (DALY)	1.158E+03	3.339E+03	5.181E+03	5.008E+03
30. Large accident fatalities (fatalities)	2.809E+00	8.558E-01	9.772E-02	6.340E-02
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe)	1.722E+07	6.068E+07	1.067E+08	9.653E+07
36. Diversity of fuel supply (dimensionless)	8.361E+01	8.920E+01	9.237E+01	9.188E+01
37. Fuel storage capabilities (GJ/m^3)	1.505E+06	4.363E+06	4.863E+06	5.190E+06
38. Nuclear proliferation (ordinal scale)	4.791E+00	1.389E+01	1.548E+01	1.652E+01
39. Depletion of elements (kg Sb eq.)	8.608E+04	3.400E+05	7.488E+05	8.031E+05
40. Depletion of fossil fuels (MJ)	2.399E+12	7.065E+11	1.074E+11	9.455E+10
41. Volume of radwaste to be stored (m^3)	5.196E+02	1.641E+03	2.549E+03	2.459E+03
42. Volume of liquid CO_2 to be stored (m^3)	7.912E+06	2.299E+07	1.602E+06	7.237E+05

19.5.4 Techno-economic results (per unit of electricity generated)

	2020	2035	2050	2070
1. Capacity factor (%)	6.289E+01	6.402E+01	6.005E+01	5.967E+01
2. Availability factor (%)	8.640E+01	9.117E+01	9.240E+01	9.222E+01
3. Technical dispatch. (no units)	8.415E+00	1.188E+01	1.346E+01	1.330E+01
4. Economic dispatch. (no units)	3.844E+01	6.752E+01	7.829E+01	7.900E+01
5. Lifetime of fuel reserves (yrs)	1.604E+02	4.046E+02	5.461E+02	5.071E+02
6. Technological lock-in resistance (yrs^{-1})	1.022E+01	3.494E+00	8.189E-01	8.539E-01
7. Time to start-up (months)	4.244E+01	4.214E+01	3.692E+01	3.812E+01
8. Levelised cost: capital (£/MWh)	3.193E+01	6.850E+01	7.811E+01	7.343E+01
9. Levelised cost: O&M (£/MWh)	9.910E+00	1.782E+01	1.777E+01	1.560E+01
10. Levelised cost: fuel (£/MWh)	3.054E+01	1.066E+01	2.528E+00	2.647E+00
11. Levelised cost: TOTAL (£/MWh)	7.233E+01	9.696E+01	9.840E+01	9.168E+01
12. Fuel price sensitivity (%)	4.572E+01	1.475E+01	3.707E+00	3.907E+00
13. Financial incentives (£/MWh)	n/a	n/a	n/a	n/a

19.5.5 Environmental results (per unit of electricity generated)

	2020	2035	2050	2070
14. Recyclability (ratio)	8.785E-01	8.923E-01	9.086E-01	9.028E-01
15. Freshwater eco-toxicity (kg DCB eq./kWh)	1.024E-02	1.438E-02	1.485E-02	1.531E-02
16. Marine eco-toxicity (kg DCB eq./kWh)	1.631E+02	6.677E+01	3.486E+01	3.565E+01
17. Global warming (kg CO_2 eq./kWh)	4.451E-01	7.183E-02	1.293E-02	1.407E-02

18. Ozone layer depletion (kg CFC-11 eq./kWh)	7.720E-09	3.166E-09	1.773E-09	2.081E-09
19. Acidification (kg SO_2 eq./kWh)	5.417E-04	1.556E-04	7.884E-05	8.487E-05
20. Eutrophication (kg PO_4^{3-} eq./kWh)	8.748E-05	2.725E-05	2.118E-05	2.141E-05
21. Photochemical smog (kg C_2H_4 eq./kWh)	5.101E-05	1.735E-05	1.008E-05	1.121E-05
22. Land occupation (m^2yr/kWh)	7.677E-03	2.715E-03	8.752E-04	9.334E-04
23. Greenfield land use (ratio)	n/a	n/a	n/a	n/a
24. Terrestrial eco-toxicity (kg DCB eq./kWh)	7.119E-04	7.632E-04	6.885E-04	6.887E-04

19.5.6 Social results (per unit of electricity generated)

	2020	2035	2050	2070
25. Direct employment (person-yrs/TWh)	6.112E+01	1.092E+02	1.251E+02	1.113E+02
26. Total employment (person-yrs/TWh)	1.232E+02	1.498E+02	1.563E+02	1.401E+02
27. Worker injuries (injuries/TWh)	8.889E-01	4.336E-01	2.489E-01	2.298E-01
28. Human toxicity potential (kg DCB eq./kWh)	4.745E-02	7.383E-02	7.627E-02	8.010E-02
29. Health impacts from radiation (DALY/kWh)	3.287E-09	8.698E-09	9.682E-09	1.036E-08
30. Large accident fatalities (fatalities/PWh)	7.971E+00	2.229E+00	1.826E-01	1.311E-01
31. Staff hired from local community (%)	n/a	n/a	n/a	n/a
32. Spending on local suppliers (%)	n/a	n/a	n/a	n/a
33. Investment in local community (%)	n/a	n/a	n/a	n/a
34. Human rights and corruption (ordinal scale)	n/a	n/a	n/a	n/a
35. Fossil fuel avoided (toe/kWh)	4.886E-05	1.581E-04	1.993E-04	1.996E-04
36. Diversity of fuel supply (dimensionless)	8.361E+01	8.920E+01	9.237E+01	9.188E+01
37. Fuel storage capabilities (GJ/m^3)	1.505E+06	4.363E+06	4.863E+06	5.190E+06
38. Nuclear proliferation (ordinal scale)	4.791E+00	1.389E+01	1.548E+01	1.652E+01
39. Depletion of elements (kg Sb eq./kWh)	2.443E-07	8.858E-07	1.399E-06	1.661E-06
40. Depletion of fossil fuels (MJ/kWh)	6.808E+00	1.840E+00	2.006E-01	1.955E-01
41. Volume of radwaste to be stored (m^3/TWh)	1.475E+00	4.275E+00	4.764E+00	5.085E+00
42. Volume of liquid CO_2 to be stored (m^3/MWh)	2.245E-02	5.987E-02	2.994E-03	1.497E-03