Comparative analysis of electricity generating technologies with regards to environmental burdens

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Comparative analysis of electricity generating technologies with regards to environmental burdens

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Signed…………………………………………………….

ABSTRACT

In the last couple of decades, there has been an increased awareness of the effects that electricity generation has on the environment through the emission of greenhouse gases and the depletion of natural resources. This realisation, coupled with an increased drive towards ensuring the sustainability of the energy supply system, has lead many, including the United Kingdom government to investigate the options for moving away from traditional fossil fuel-burning generation methods towards “low-carbon” generators, such as renewables and nuclear power. Specifically, wind power, the more mature systems (with the exception of hydro power) of the available renewable energy supply, and nuclear power, a technology seen as producing large amounts of electricity with very few associated greenhouse emissions, have been promoted but also pitted against each other by analysts and policy makers.

This work aims to provide a balanced analysis of wind power and nuclear power with respect to their effects on the natural environment. As such, modeling has been undertaken of a Generation III+ nuclear reactor, an onshore wind farm located in southern Scotland and an offshore wind farm near the Thames estuary while environmental indicators have been created to permit the comparative assessment of these three electricity generation technologies, in a U.K. context. These indicators thus facilitate an assessment of the energy requirements, the associated greenhouse gas emissions, the natural resource requirements, as well as the displaced carbon dioxide emissions from operation of each power plant. A parametric analysis has also been conducted to show the range of likely variations in each indicator’s values.

The results of this research show that all three technologies demonstrate similar performance with respect to their energetic and environmental impacts. More specifically, the wind farms demonstrate better energy gain ratios than the nuclear power plant when they are credited for not depleting non-renewable fuel sources. The wind farms also are shown to pay back their energy investments faster than the nuclear power plant. On the other hand, the nuclear power plant is found to produce slightly lower greenhouse gas emissions than either onshore or offshore wind farms. With respect to the assessment of natural resource depletion, it is estimated that both wind farms need more land per unit of electricity produced than the nuclear power plant, but all three power plants permanently sequester similar amounts of water. The wind farms and the nuclear power plant are found to have similar performance with respect to their material requirements, while the calculation of the avoided emissions factors for all technologies are of similar orders of magnitude.

All results are shown to be highly sensitive to the assumptions made about the prospective lifecycles, and as such caution should be exercised when drawing conclusions about any comparative advantages. Nethertheless both technologies are clearly shown to have lower environmental impacts than traditional electricity generation technologies.

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A big thank you also goes out to all my collegues in the 'Sustainable Energy Research Team' at the university and my friends from Bath, who have been there constantly throughout my many years as a student and afterwards.

I would like to dedicate this thesis to the memory of my father, Christos Papadopoulos, who was a source of neverending encouragement and support, but did not live long enough to see the completion of this work.

Πατέρα, το τελείωσα για σένα...

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Glossary and Abbreviations

AC	Alternating current.
AGR	Advanced Gas Reactor; type of nuclear reactor, see Section 4.2.2.
Ambient energy	Natural energy flows such as solar, wind, and wave energy
Back End	All activities encompassed in the final stages of a process.
Baseload generation	Method of operation of a power station at a constant high level of output for sustained periods of time to assist in meeting minimum national demand.
BERR	The UK's 'Department for Business, Enterprise and Regulatory Reform'; formerly the 'DTI' (see below).
BWEA	British Wind Energy Association.
BWR	Boiling Water Reactor; type of nuclear reactor, see Section 4.2.2.
CAES	Compressed Air Energy Storage
CANDU	Type of nuclear reactor, of Canadian design; see Section 4.2.2.
CCGT	Closed Cycle Gas Turbine
CED	Cumulative Energy Demand; defined in 3.5.1.5
CEGB	Central Electricity Generating Board.
CHP	Combined Heat and Power
DC	Direct current.
DECC	Department of Energy and Climate Change. U.K. government department. set up to bring together energy and climate change mitigation policy making, previously undertaken at BERR and DEFRA.
DEFRA	UK government department responsible for policy and regulations on the environment, food and rural affairs
Delivered Energy	Energy carriers (e.g. fuel or electricity) delivered to the end-user.
DTI	The UK's 'Department of Trade and Industry', now 'BERR' (see above).
EA	Energy Analysis. Method of energy accounting (see 2.3.1)
EC	European Commission
EEC	European Economic Comunity
Embodied carbon	The total (direct and indirect) carbon-dioxide equivalent emissions associated with a product or activity at the point of either production or delivery to the end-user.

Embodied energy	The total (direct and indirect) energy requirement a product or activity at the point of either production or delivery to the end-user.
Energy carrier	A method of storing energy or transporting it from place to place, usually by implication under human control; covers all fuels plus electricity.
Energy Density	Energy density is a term used for the amount of energy stored in a given system or region of space per unit of measurement.
Energy (end) product	A final energy result that can be used directly, especially one resulting from a series of stages or processes
ERE	Energy requirement for energy The gross energy requirement of an energy carrier, per unit of that energy carrier
Energy resource	A source of useable power, which can be drawn on when needed. Energy resources are often classified as renewable or non-renewable
Enthalpy	A thermodynamic property that equals the sum of a fluid's *internal energy* and its *pressure* multiplied by its *volume.*
Enthalpy of combustion	The difference between the enthalpy of the products of combustion and the enthalpy of the reactants, each on a per mole of fuel basis, when complete combustion occurs and both reactants and products are at the same temperature and pressure. The magnitude of the enthalpy of combustion is referred to as the 'calorific value', and two forms are recognised: the gross calorific value (GCV) and the net calorific value (NCV). The GCV is obtained when all the water formed by combustion is a liquid; the NCV is obtained when all the water formed by combustion is a vapour.
EPD	Environmental Product Declaration. A system based on certified environmental declarations (see 2.3.3.1)
EU	European Union
EURATOM	European institution responcible for nuclear fuel supply management
Front End	All activities encompassed in the initial stages of a process.
Fuel oil	The heavy oils from the refining process; used as fuel in furnaces and boilers of power stations, industry, in domestic and industrial heating, ships, locomotives, metallurgic operations, and industrial power plants etc.
GCV	Gross calorific value, also referred to in the literature as 'higher heating value' (HHV).

GHG	Greenhouse gas, here measured in ‘carbon-dioxide equivalent’ terms.
GER	Gross energy requirement. The sum of all the energy resources that had to be sequestered in order to produce the product or service. This includes the energy that may be ‘tied up’ in the finished product in addition to the energy used during production.
HAWT	Horizontal-axis wind turbine.
Heat engine	An engine that converts heat input into work output via a cyclic process.
HLW	High level waste; see Section 4.2.7.2
HM	Heavy Metals; uranium dioxide,Plutonium and other isotopes found in nuclear by-products.
IEA	International Energy Agency
IAEA	International Atomic Energy Agency.
ILW	Intermediate Level Waste; see Section 4.2.7.2
I/O	Input-Output Analysis. Method of energy accounting (see 2.3.1)
Irreversible Process	Opposite of ‘reversible process’
ISL	In-situ leaching; method of mineral extraction; see Section 4.2.5.1
LCA	Life Cycle Assessment. Method of accounting all inputs and outputs to a product life cycle (see 2.3.3)
LLW	Low Level Waste; see Section 4.2.7.2
MAGNOX	Type of nuclear reactor; see Section 4.2.2
Met. Office	Official name of the UK’s national weather service.
NCV	Net calorific value, also referred to as ‘lower heating value’ (LHV).
NEA	Net Energy Analysis. Method of energy accounting (see 2.3.2)
NER	Net energy requirement**.**The net energy requirement is the gross energy requirement minus any energy still available in the product of interest.
NOABL	Department of Trade and Industry wind speed database
NPP	Abbeviation used in thesis for Nuclear Power Plant.
OECD	Organisation for Economic Co-operation and Development
PA	Process Analysis. Method of energy accounting (see 2.3.1)
PGRC	Phased Geological Repository Concept; see Section 4.2.7.8
Primary energy	Energy that is ‘drawn (extracted or captured) from natural reserves or flows’.

PV	Abbreviation for photovoltaic cells; panels made of semiconducting materials which produce electricity when exposed to sunlight.
Reversible process	A process is reversible if it is possible to return to its initial conditions.
RBMK	Type of nuclear reactor, developed in the Soviet Union; see Section 4.2.2
SF	Spent fuel; see Section 4.2.7.2
SWU	The SWU is a complex unit which is a function of the amount of uranium processed and the degree to which it is enriched and the level of depletion of the remainder (i.e. depleted uranium).
UF_6	Uranium hexafluoride
UO_2	Uranium dioxide
VAWT	Vertical-axis wind turbine.
WAsP	Wind Atlas Analysis and Application Program
Yellowcake	A concentrated form of uranium ore containing a mixture of oxides.

1. Introduction

1.1 Energy and the Environment – Setting the Scene

Energy is at the heart of virtually every human activity. It is used in transportation, to generate heat and to power the multitude of various devices that make our current way of life possible. It has subsequently been argued that the evolution of the human society has been directly linked with the discovery and utilisation of energy sources (Hammond 2001). Early societies used wood and agricultural residues to generate heat while most other activities were underpinned by the expenditure of energy in the form of "muscle" power. As societies developed, so did the need for larger quantities of energy to facilitate human development. This led to the development of large scale energy supply systems which in turn facilitated the expansion of energy use and resulted in an associated increase in human development (Patterson 1999). An energy supply system is a system that encompasses the *fuel sources* and the *processes* that are required to transform those fuel sources into a useable *energy product,* which can be either in the form of heat or power. The *processes* encompassed in this definition include all aspects of fuel source manipulation, whether extracting, refining or transporting the fuel source, as well as the actual conversion technologies required for the generation of heat and/or power.

The main sources of the energy can be divided into the so-called "non-renewable" and "renewable" sources. The first category encompasses the sources also known as "fossil" fuels which are the result of the deposition of organic matter over a long period of time such as coal, natural gas and oil in all its forms. The group of non-renewable energy sources also includes non-fossil fuels such as uranium ores, which although not the result of organic matter transformations, are limited in their supply and by their nature as they are subject to the laws of radioactive decay (Boyle 2004). The category of renewable energy sources, on the other hand, can be defined by a variety of factors. A general description would be that renewable energy sources are energy sources which are obtained from continuous energy currents recurring in nature and are replenished at a similar rate to that of their depletion. Most renewable energy sources are solar-derived either directly, such as in the case of solar irradiation (heating or converting sunlight to electricity) or indirectly, such as wind, wave, running water and biomass (wood, straw, dung and plant wastes). Other sources of renewable energy are either derived from the Earth's gravity such as tidal sources of energy, or from the Earth's rotation such as geothermal energy (Boyle 2004).

Since the industrial revolution in the late 18th century, energy sources have been harnessed on an ever increasing scale. It is interesting to note that in the pre-industrialised period of human history, human society was effectively powered by what are now defined as "renewable" energy sources. This was of course possible because the societies of the time had low energy demands but at the same time, it was necessary to utilise the energy sources in the immediate area of their extraction as there was no way to transport the energy sources or their resulting products (mostly heat) over any distance. The development of advanced industrialised societies however, was based on the utilisation of fossil fuel resources and the development of their associated energy supply systems (Elliott 2003). Arguably, the fossil fuel that drove the British "Industrial Revolution" was coal, which coincided with the advent of the steam engine. These initial advances were followed by the invention of the internal combustion engine, which also saw the rise of another fossil fuel, namely that of oil and all its resulting forms.

Another form of energy that gained prominence in the 19th century is electricity. Based on the works of scientists such as Alessandro Volta, Georg Ohm, André Ampère and Michael Faraday amongst others, the practical applications of electricity were soon realised and from the end of that century with the invention of the incandescent lightbulb, electricity started to play a significant role in everyday life. Although the original networks for providing electricity were small scale ventures designed to provide electricity to local end users, following the end of the First World War more centralised generation and distribution systems emerged, which were designed to cater for the increase in demand, as well as scale. These distribution networks were based on the concept of large centralised electricity-generating plants using a network of cables to distribute the electricity they produced to end users attached to the system (Patterson 1999). Since these times and especially during the 20th century, the rate of worldwide energy use has increased nine-fold, with the most rapid growth in energy demand being that for electricity and fuels for mobility (Royal Commission on Environmental Pollution 2000).

1.1.1 U.K. historical perspective

From a U.K. perspective the development of the energy sector, especially post-World War II, was influenced by a variety of factors. Coal reserves in the country were plentiful and cheap petroleum supplies were readily available, principally from the Middle East. Solid fuels (coal, coke and breeze) were the main source of energy for home heating, in industry and for electricity generation. Although oil dominated the transport sector it also increasingly gained a role in other sectors such as electricity generation. As such, it could be argued that economic growth in Europe, as well as the in U.K., during the 1960s was mainly fuelled by coal and to an increasing extent by oil. Two-thirds of the latter was imported from Arab countries, and this dependence on a single source subsequently set the scene for further fundamental changes. Following the Yom Kippur War in October 1973, Saudi Arabia imposed an oil embargo on certain countries (namely the United States and the Netherlands), which ultimately led to a cut of 17 per cent in output from the members of the Organization of Petroleum Exporting Countries (OPEC) resulting in a significant effect on the price of oil (Hammond 1998). The result of this reduction in oil supplies and the connected price increase sent shock waves through western industrialised economies and measures were subsequently adopted to reduce the dependence on imported oil (Hammond 1996). The U.K.'s efforts focused on the development of the oil and natural gas fields discovered in the North Sea, which made the nation self sufficient and ensured that natural gas was adopted for an increasing number of uses, including that of electricity generation. As a result of the North Sea supplies, the relatively cheap price of natural gas and the low capital cost of combined cycle gas turbine (CCGT) generators meant that the adoption of this type of power plant technology expanded rapidly. The result of this decision was the so-called 'dash for gas', which outstripped even most contemporary predictions (Hammond 2001). Arguably however, the highest level of development was experienced by the civil nuclear power programme, especially from the 1960s onwards. Nuclear power was originally seen as an important energy source that was potentially 'clean, cheap and abundant' making it a direct rival to traditional fossil fuels for electricity generation.

Globally, the adoption of this energy supply system was greatest in countries such as Belgium and France which had relatively few indigenous fossil fuel resources while in the United Kingdom, nuclear power briefly became the largest generator with a 36 per cent share by 1997 (Hammond 2001). However, the further adoption of nuclear power was significantly affected in the aftermath of the Three Mile Island incident (1979) and more importantly the explosion at the Chernobyl power plant in what is now the Ukraine, in 1986. These events combined with the realisation that nuclear power was not as cheap as originally projected led ultimately to the decline of the electricity generation share nuclear power held in various, mainly western, countries (Hammond 1996).

Other energy supply systems that were positively influenced by the “oil crises” of the 1970s were those based on renewable energy sources. As previously mentioned, these encompassed systems which are based on natural energy sources such as wind, water and solar, of which wind power specifically has a long standing history in the United Kingdom. Despite individual projects being around since the late 1800s, it wasn’t until governmental support was introduced in the early 1990s (in the form of the Non Fossil Fuel Obligation or NFFO), that wind power took off in a substantial way. Since then, further support has allowed the technology to grow exponentially, with wind power becoming, in 2008, the largest generator by installed capacity in the UK (DTI 2008).

1.1.2 Fuel used for electricity generation

Despite the oil shocks and the upsurge in interest in alternative methods of electricity and more generally energy production, renewable energy sources and technologies have remained in their infancy, with the exception of hydro power which has provided a large percentage of worldwide electricity supplies and in certain countries still remains the largest single contributor. Thus, in almost all industrialised nations, fossil fuels remain the main sources for electricity generation (Elliott 2003). This fact is illustrated below, in Figure 1.1, which shows the fuel sources used for electricity generation, worldwide (IEA 2010).

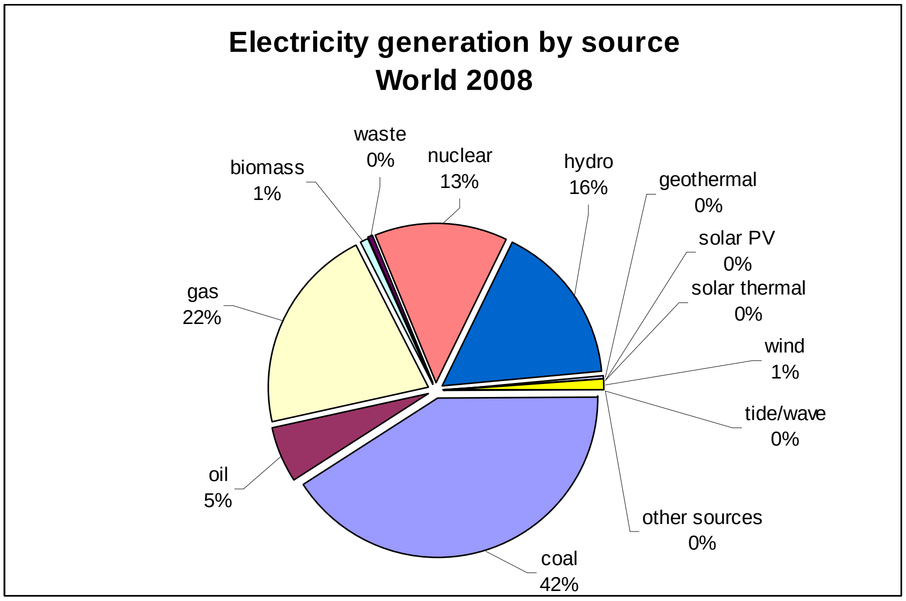


Figure 1.1 Breakdown of electricity generation by source worldwide in 2008

A similar representation for the United Kingdom alone shows a similar trend, but with a higher reliance on natural gas and nuclear, as can be seen in Figure 1.2. Based on this data, approximately 74% of electricity produced is from fossil fuel sources, with a large percentage of that coming from coal-fired generation, which is almost universally agreed to be the most carbon intensive method of producing electricity (Sustainable Development Commission 2006b).

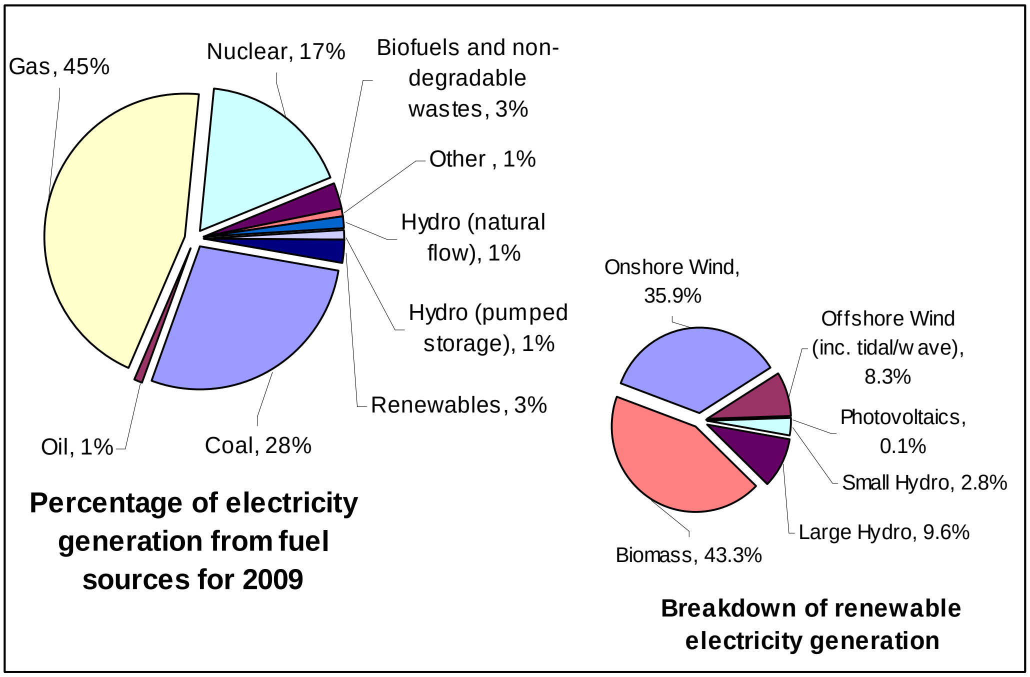


Figure 1.2 Breakdown of electricity supplied by source in the U.K. in 2009

From the above data (DECC 2010), it can clearly be seen that, in the U.K. and worldwide, electricity production is heavily reliant of the burning of fossil fuels. It is also noted that from the available renewable sources, only wind and hydro have significant shares in the total electricity production sector. This reliance on fossil fuels, however, has become an increasingly problematic as a result of two interrelated issues, namely Climate Change and need to progress towards Sustainable Development. These two issues are explored in more detail in the following sections and provide the impetus for this current research, by creating the framework within which the comparison of different energy supply systems were assessed.

1.2 Climate Change

The benefits of electricity generation and use are easy to identify as they have become integral to the way of living in most of the industrialised world. However, it has long been observed that the extraction, refining, transportation and end-use of fossil fuels can have adverse effects on the environment. Energy sources of various kinds empower human development, but also place the quality and long term sustainability of such development at risk, through the generation of “side-effects” on a regional and global scale. The negative impacts of fossil fuel power generation on society, on a local scale, have been well documented (examples include the smog affecting London during the 1950s and California near the end of the last century). Recently however, a new awareness of the impacts that energy generation (which naturally includes electricity generation) and use have on the planet has emerged. These impacts arise from the emission of carbon dioxide and other greenhouse gases that cause the phenomenon known as the “Greenhouse Effect”. It is a generally accepted fact among the scientific community that the concentration of greenhouse gases in the Earth’s atmosphere has been increasing due to human activities, as described in the Intergovernmental panel of Climate Change (IPCC) 2001 report (IPCC 2001).

The IPCC 2001 report (IPCC 2001) claimed that over the past century global temperatures have risen by some 0.7 deg C on average, and there is strong evidence to suggest that the primary cause of this is an increase in greenhouse gases in the atmosphere due to man-made emissions, with carbon dioxide playing the most important role. Without actions to curb emissions, globally averaged temperatures are expected to rise by some 1.4 to 5.8 deg C and sea levels by between 9 and 88 cm during this century, with increasingly severe impacts on the natural world and society. As temperatures rise the risk of more major climate disruption over the longer term will increase, such as melting of the Greenland ice-sheet or changes to the North Atlantic Ocean Circulation that gives the UK its mild climate (IPCC 2001). In the follow up study, published in 2007, the IPCC proceed to state that “Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level” while “Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations” (IPCC 2007a).

In recognition of the global nature of the problem, the United Nations Framework Convention on Climate Change (UNFCCC) was agreed upon at the Earth Summit in Rio de Janeiro in 1992. The UNFCCC set the overarching objective for multilateral action: to stabilise greenhouse gas concentrations in the atmosphere at a level that avoids dangerous anthropogenic climate change. In 1997, EU Member States agreed that a global average temperature increase of no more than 2 degrees ºC above pre-industrial levels would be desirable and therefore, as estimated at the time, a concentration below 550 parts per million of CO_2 to prevent the most damaging effects of climate change. This reinforced the case for urgent and committed multilateral international action, which the Kyoto Protocol, agreed in December 1997, sought to address. Developed countries agreed to reduce their overall emissions of a basket of six greenhouse gases by 5.2 per cent below 1990 levels over the period 2008-2012, with differentiated, legally binding targets.

As previously discussed, modern civilisation depends, to a very large degree, on the burning of fossil fuels to generate heat and power. However, given the accumulating evidence, the world community has had to confront the fact that it cannot continue with the current status quo in power generation. As a result of this realisation, the global community is currently in the process of trying to move away from its dependence on fossil fuels and move towards the development of alternative sources of energy, which are considered to be more environmentally benign (Boyle 2004).

1.2.1 Emissions statistics for the United Kingdom

Currently, it is estimated that the UK emissions represent approximately 2% of total global emissions (DTI 2006a). In the 2003 Energy White Paper, the UK government committed itself to putting the U.K. on a path to cut CO_2 emissions by some 60% by

2050, as recommended by the Royal Commission on Environmental Pollution, and to achieving ‘real progress’ by 2020. Under the Kyoto Protocol, the UK’s contribution is to reduce greenhouse gas emissions by 12.5% below base year levels by 2008-12. The second goal in the shorter term was to reduce CO_2 emissions by 20% on the 1990 level by 2010. These targets were reiterated in the 2006 Energy Review, which also provided the Government’s plans for the Emissions Trading Scheme (ETS), energy efficiency and energy security amongst others.

In 2007, the U.K. Government published a further energy White Paper (DTI 2007b) prompted in part by the recommendations of the Stern Review (Stern 2006) which concluded that in the long-term the cost of inaction would be far higher than the cost of tackling climate change now. In this White Paper, the Government proposed the drafting of the Climate Change Bill which would provide a legal framework to achieve at least a 60% reduction in carbon dioxide emissions by 2050, and a 26-32% reduction by 2020, against a 1990 baseline (DTI 2007b). Some commentators have postulated as a result of the above targets, that given the likely innovations in other sectors, the electricity sector could be required to reduce its emissions by as much as 90% by 2050 (Odenberger & Johnsson 2007). Following further discussions and assessments, the U.K. Climate Change Bill was made an Act of Parliament, mandating the reduction of all six greenhouse gases specified by the Kyoto Accord by 80% by 2050, compared to the 1990 levels (HM Government, 2008). Subsequent to this, the U.K. Government published the Low Carbon Transition Plan, which detailed the actions that should be taken to achieve a 34% decrease in carbon emissions by 2020 (HM Government, 2009).

A sectoral analysis of UK greenhouse gas emissions can help to illustrate where emissions are coming from and what is driving them. The energy supply sector currently accounts for around 35% of emissions; transport for 24%; industry 22%; services 4% and the residential sector 15% (DTI 2006a). From these figures it is obvious that the energy sector represents approximately a third of all U.K. related emissions. The 2007 White Paper also indicates that in 2005, electricity generation was responsible for 40% of the global carbon dioxide emissions (DTI 2007b).

As a result of the above estimates, there has been an increasing focus on the reduction of emissions throughout the energy sector, through the adoption of low or near-zero carbon technologies for the generation of electricity. An important consequence of this has been the elevated importance of the assessment of greenhouse gases in the evaluation of electricity generation technologies. This is turn, has formed the basis for some of the metrics of comparison used in this current work.

1.3 Sustainable Development

In recent years, the terms “Sustainability” and “Sustainable Development” have been coined to describe the long-term viability and effects of human endeavours. In the words of the “Brundtland Commission” report, published in 1987 at the Stockholm Conference, "*sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED 1987). An alternative representation of sustainability, with greater relevance to engineering, has been promoted by Parkin (Parkin 2000) who argued that thermodynamic analyses underlie the concept of Sustainable Development more broadly. Hammond, however, has argued that the use of thermodynamics must be seen as a metaphor, since its use to define criteria for long term sustainability can be misleading (Hammond 2007a).

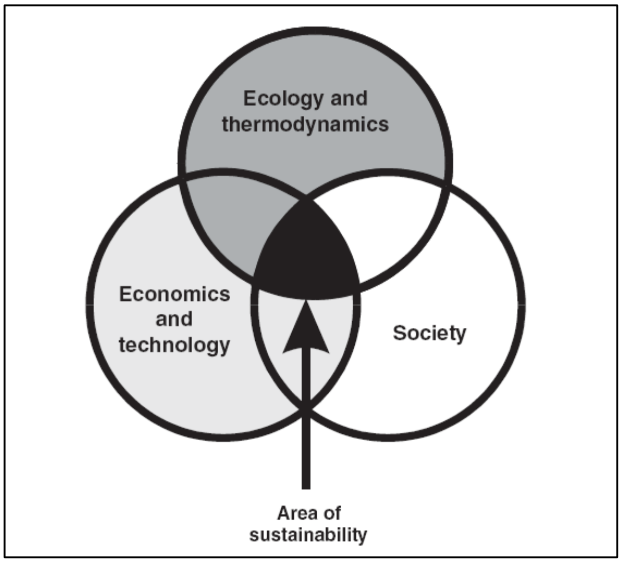


Figure 1.3 Sustainability 'Venn' diagram

As can be seen in the above diagram ((Hammond 2004), adapted from (Parkin 2000)), the concept of sustainability requires a consideration of a broader basis, which included societal and techno-economic criteria as well as environmental ones. This has helped define a broad framework of assessment for various systems, including those devoted to energy and, by default, electricity production.

1.3.1 Sustainable Development and the energy sector

Energy is linked to all three dimensions of Sustainable Development as defined in Figure 1.3 and specifically it can be argued that energy services are directly connected to economic and social development. As a result of this, and given that there is a link between the two, energy requirements are expected to continue to increase and as such so will the environmental impacts (Salman 2006;UNDP 2005). Thus, it is essential that the impacts are controlled, alleviated or mitigated in order to achieve sustainable development goals. It has been stated that the main challenge for the energy sector, with respect to the dictates of sustainable development, is to provide the benefits of energy to current and future generations, “without undermining the essential life support systems or the carrying capacity of the environment” (NEA & OECD 2001).

The conclusion from the definition of sustainability, as defined by the Brundtland Commission, is of special interest to the energy and, specifically, the electricity sector. As it calls for a halt to actions that degrade the biosphere, it effectively implies the need for conserving fossil fuel resources and making greater use of renewables (Hammond 2004). It has also been argued that nuclear power has a role to play according to the above definition (NEA & OECD 2001).

In 2006, the European Commission published a Green Paper entitled “A European Strategy for Sustainable, Competitive and Secure Energy”, which outlined the priorities the EU should set itself within the framework of energy supply. The first conclusion drawn from the report was related to sustainability and stipulated the development of renewable energy sources as well as other low carbon sources as the path to halting climate change (Commision of the European Communities 2006).

The group of renewable energy sources and low-carbon technologies contains a broad range of options and is not clearly defined. The category of "low carbon" emitters especially has been open to considerable debate, as will be seen in following sections. Whatever the exact boundaries of each category however, what has become apparent is that wind power and nuclear power are among the main candidates worldwide to help address the need for emission reductions in electricity generation, the former because of its ever increasing share in renewable electricity generation as can be seen in Figure 1.2, and the latter because of its projected utility as a large scale source of low carbon electricity. The relative position of both wind and nuclear power has been widely debated, especially from the position of environmental "friendliness" or "benighness". While nuclear power is generally considered to be the least environmentally-friendly technology of the two (see publications such as Campaign for nuclear disarmament 2006a, Jan Willem Storm van Leeuwen & Philip Smith 2005, Roche 2005) there has also been research conducted into the negative effects renewables can have on the environment (International Energy Agency 1998, Rashad & Hammad 2000, CEC et al. 1995, Inhaber 1978). Although wind power, and renewable energy sources in general, are considered inherently sustainable, nuclear power's position has been less clear. Although it has been argued that nuclear fuel cycle cannot be sustainable due to the fact that it is based on the conversion of uranium (and other radioactive ores), which are themselves depletable, some commentators have promoted the idea that nuclear power can be sustainable under certain conditions. Most commentators base this approach on the utilisation of nuclear fuel recycling as well as the use of novel reactors cycles (such as Fast Breeder reactors) (NEA & OECD 2001). Others have promoted the combination of nuclear generation with hydrogen production (Yamawaki et al.), as a means of extending the productivity of the fuel cycle. Another approach has been to argue the sustainability of nuclear fuel cycles by using a more broad definition of the aims and limitations of the concept. From this viewpoint, one of the main goals of Sustainable Development is to maintain or increase the overall assets (natural, man-made and human or social assets) available to future generations, while allowing some trade-offs and substitutions between these assets (also termed "weak sustainability"). Thus, since the development of nuclear energy broadens the natural resource base useable for energy production, and increases human and man-made capital, it can effectively be considered sustainable (NEA & OECD 2001). Put differently, "a major goal of sustainable development is bringing energy, especially electricity, to the quarter of the world's population now without it" (IAEA 2006). Work carried out using scenario based analysis has argued that nuclear power can contribute both to tackling climate change as well as meeting the aims of sustainability (Nuclear Energy Agency 2006;Weisser, Howells, & Rogner 2008)

1.4 Reasons for the comparative study of nuclear and wind

The previous sections have highlighted the overall reasons that make the assessment of electricity generating technologies necessary and topical, by outlining the historical development of the sector and the current drivers for change. The sections that follow, on the other hand, seek to illustrate the need for the *comparative* analysis of the two energy supply systems investigated in this work, namely nuclear and wind power.

1.4.1 Policy Background

The Energy White Paper, entitled "Our Energy Future" and published in 2003, apart from highlighting the UK's commitment to the Kyoto Protocol, outlined what issues the Government considered important as well as their proposals for tackling future energy issues. Apart from illustrating the need for better energy efficiency, measures to deal with "energy poverty" and a reduction of emission from the transport, housing and public sector, the Paper also made one of its priorities the reduction of emission from the energy sector while at the same time ensuring energy security. Based on 2002 estimates, renewables only accounted for 3% of the UK electricity generation, with nuclear adding 23% and coal, oil and gas totaling 75%. The guidelines proposed were seen as an endorsement for forms of renewable energy since they were perceived as carbon-free or at least carbon-neutral. At the same time, there was no direct decision on the future of nuclear power in the United Kingdom, even though it was stated that "…if new nuclear power plants are needed to help meet the UK's carbon aims, this will be subject to later decision" (DTI 2003)

The issue of energy security has also become more prominent with the decline in the UK's current indigenous energy resources. It was predicted that by 2020 the United Kingdom could be dependent on imports for three quarters of its primary energy imputs (DTI 2003). The potential dangers of over-reliance on imported energy sources was brought dramatically into perspective in the winter of 2006, when a dispute over natural gas pricing arose between the Russian state-owned gas utility Gazprom and the Ukraine. This dispute led the Russian Federation to cut off supplies to the Ukraine, which also had a knock on effect for the rest of Europe. As a result of this move by Russia, Europe almost immediately experienced a shortage of natural gas supplies and the resulting price hike had substantial effects on most European economies. Despite the guidelines set out by the White Paper, there was mixed success with the policy measures set up to tackle the issues. Carbon emissions continued to rise in the following three years, mainly due to the increased use of coal in power generation required to offset the increase in gas prices as well as the increase in energy demand, despite the energy efficiency measures (Sustainable Development Commission 2006a).

These issues, coupled with mounting evidence of the effects of carbon emissions on climate change prompted the U.K. Government to publish in early 2006, a consultation paper on the future of the country's energy planning. The paper contained five key issues that it was felt, needed to be addressed in more detail. Once again, the low carbon technologies were highlighted as an area where the government wished for more development. This was underlined by the dual question of what special considerations should apply to renewables as well as what the government could do to help the growth of this sector (DTI 2006a). However, the government left open the potential of re-assessing the nuclear option. This was encouraged by various commentators, who brought forward arguments that seemed to illustrate more clearly the need for new nuclear power plants. Among the most prominent arguments were those of the security of supply that nuclear could provide, the perceived "generation gap" (with the closure of existing nuclear and coal power stations there was concern that the country would be facing a shortfall in electricity generating capacity, which renewables alone would not be able to cover) as well as the argument that nuclear power was inherently carbon-free as no CO_2 emissions were generated during the stage of electricity generation (Sustainable Development Commission 2006a).

The culmination of the evidence and opinions put forward as a result of the Energy Consultation paper led to the publication of the report, entitled “Our Energy Challenge” in July 2006. In this report, the two main issues highlighted above all others were those of energy security and the measures required to mitigate the effects of man made emissions on climate change. As in the original Energy White Paper in 2003, this report highlighted the UK’s need to meet its obligations under the Kyoto Protocol, and the Governments commitment to the development of renewable energy sources (specifically with an aim of 20% of the country’s electricity supplied by renewable sources by 2020). As implied by the Energy Consultation Paper earlier in 2006, the government indicated that it believed a new round of nuclear build would be in accordance with its aims set out in the White Paper. Specifically, it was stated that the government “…concluded that new nuclear power stations would make a significant contribution to meeting our energy policy goals.” (DTI 2006a). However, many critics felt that the Energy Review was instigated as a stepping stone for the re-introduction of nuclear power in the U.K. Certain elements of the 2006 Energy review were challenged legally by Greenpeace, leading to a High Court ruling which branded the Review as “seriously flawed” (The Guardian 2007).

The Energy White paper, “*Meeting the Energy Challenge”* published in May 2007, stated as one of its main aims “to cut the UK’s carbon dioxide emissions by some 60% by about 2050, with real progress by 2020” (DTI 2007b). The Paper also maintained that the 'preliminary view is that it is in the public interest to give the private sector the option of investing in new nuclear power stations”. To this end, a consultation process on nuclear power was initiated with the publication of the document “*The Future of Nuclear Power*” (DTI 2007c), which in effect was a response to the High Court ruling on the 2006 Energy Review. This time, following the successful completion of the consultation process, the U.K. Government gave the go-ahead for a new round of nuclear build, with release of “The White Paper on Nuclear Power: Meeting the energy challenge”(BERR 2008b), in January 2008.

At around the same time as the publication of the 2007 Energy Review, the Government started the process of drafting the “Climate Change Bill”. This Bill aimed to create the appropriate conditions to achieve a mandatory 80% cut in the UK's carbon emissions by 2050 (compared to 1990 levels), with an intermediate target of between 26% and 32% by 2020.

Following the lengthy process of consulting on nuclear power, the Government then sought to address the problem meeting of the U.K. proposed obligation of supplying 15% of the UK’s energy from renewables, as part of an E.U.-wide scheme to provide 20% of the Union’s energy needs from renewable sources by 2020. For the U.K., this in effect represented an almost a ten-fold increase in renewable energy consumption from the then current levels (as of 2008). To this end, it initiated a further consultation with the publication of the U.K. Renewable Energy Strategy consultation in June 2008.

1.4.1.1 Implications of governmental policies

From the previous sections it can be said that generally the global community is steadily coming to realise the severity of the effect human activities are having on the global climate, as well as the level of commitment, both in terms of long-term planning as well as technology, that are required to tackle the issue of climate change. As a result of these realisations, national governments, including the UK's, are in the process of investigating and investing in possible options for the future of power generation. Originally, however, many of the options were only evaluated on their environmental performance at the point of power production, but it has since been argued that any planning should also take into account all the environmental aspects of any particular fuel cycle (Boustead & Boyd 1996;Boyle 2004) .

Prior to and following the DTI's Energy Consultation Paper, there has been a renewed interest in the possible contribution of nuclear to tackling the issues raised by the government and the world community in general. There has also been considerable debate on the potential future for nuclear power, with advocates and opponents publishing a string of papers supporting or rebuffing the arguments put forward for new nuclear power stations. These arguments have been focused on (among other parameters such as economical and social considerations) whether nuclear power should be considered a carbon-free technology, and in a broader sense, be included in the same group as renewable technologies such as wind power (Mitchell & Woodman 2006). Certain proponents of nuclear power have been keen to argue that nuclear power stations should be considered as "zero-carbon" emitters, since they do not emit any carbon dioxide during operation (Rashad & Hammad 2000;Royal Society & Royal Academy of Engineering 1999;WNA 2005a). This has met with heavy criticism from various bodies which have pointed out that although the actual stage of electricity generation is essentially carbon-free, the stages required to produce the nuclear fuel (the so-called "Front End") and the activities associated with the decommissioning and storage of waste at the end-of-life ("Back End") are far from carbon-free. In the case of decreasing ore grades, or massive expansion programs, some have claimed that nuclear becomes an unsustainable option (Chapman 1975a;Jan Willem Storm van Leeuwen & Philip Smith 2005;Mortimer 1991). This has subsequently led to the need for assessing technologies over their whole life cycle. Specifically, many pro-nuclear commentators have accepted that nuclear emits CO_2, on a life-cycle basis, but that these emissions are significantly lower than those of conventional fossil fuel generation, and in the same region as those of wind and other renewables (WNA 2005a). It has been also been argued by manufacturers and other nuclear utilities, that newer reactor designs, apart from a reduction of costs, will also result in a reduction of emissions, wastes and improved electricity production efficiency (Schulz 2006;Westinghouse Electric Company LLC 2004) .

The "anti-nuclear" proponents, as well as more moderate commentators, put forward "renewables" (wind, solar, hydro and in some cases biomass) as a viable alternative to nuclear power for electricity generation. The main renewables-based technology proposed is wind power. Certain commentators have proclaimed that wind power could meet a significant portion of future electricity demand (BWEA 2006;Greenpeace & Global Wind Energy Council 2005), while particularly in the U.K. the potential for wind power has been clearly highlighted by many studies (BWEA 2006; Tavner 2008; Sustainable Development Commission 2005). Wind power is considered the most "mature" of the renewable technology portfolio (with the exception of Hydro power plants). Wind power however has been plagued by questions of reliability of supply and whether it is as "carbon-free" as claimed, especially if storage and/or dedicated back-up capacity from the Grid is required. These questions have been partially addressed by a recent report, which illustrates that if wind power penetration is kept under a certain percentage of the total Grid supply, there is no need for a dedicated "back-up" supply to cover the times when the wind is not blowing (UKERC et al. 2006).

Certain commentators have argued the need for both wind power and nuclear power to tackle Climate Change e.g. (Fells 2002), and some have even supported the view that they are complementary (Hansen & Skinner 2005). Various scenarios have been proposed on a U.K., European and even worldwide scale, with an emphasis on one or the other technology. Certain analyses have presented scenarios with a backbone of nuclear generated power (Ernst & Young LLP 2008), while others have created scenarios that are either heavily based on renewable generation (Pöyry Energy Consulting 2008) or, in more extreme cases, that would see the phasing out of all fossil fuel based generation as well as nuclear power (Greenpeace International 2005; Greenpeace & Global Wind Energy Council 2005).

The U.K. Government published scenarios with the 2003 White Paper (DTI 2003) which included only a marginal share of nuclear generation. However, by the time of the 2007 White Paper (DTI 2007b), the contribution of nuclear had been reassessed as had the percentage that renewables would contribute to the targets. In all cases however, there is a clear need for at least one or the other technology (and in most cases both) to be present in order to meet the challenges of cutting emissions by the prescribed amounts.

Conversely, some analysts have argued that wind and nuclear are in effect, mutually exclusive (Verbruggen 2008; Mitchell & Woodman 2006). This argument has been based mostly on grounds of sustainability, financial investment and electricity system architecture. The environmental organisation Friends of the Earth has also published work claiming that nuclear power will not only fail to contribute to combating climate change but has gone on to claim that it could be "counter-productive because subsidies given to nuclear power could achieve greater emissions reductions if spent else where" (Friends of the Earth 2006). Others, on the other hand, have gone so far as to claim that renewables cannot be characterised as "environmentally friendly" since they have significant indirect impacts on their surroundings, while nuclear is "green and sustainable" especially when combined with hydrogen production (Ausubel 2007).

As such, the question still remains as to whether nuclear power with its next generation of nuclear reactors (Generation III+), is in a position to compete with renewables and specifically wind power, with regards to the greenhouse gas emissions. This criterion, as a first step, can be seen as an indication of which technology would have the "upper hand" in a choice for future power generation, if viewed purely from the perspective of emission reductions. Naturally, any such decision would be subject to a host of other parameters, which would have to be weighted depending on the priorities at the time of the decision. Given, however, the current emphasis on the reduction of emissions as a driver for averting catastrophic climate change, it is essential that the technologies in question should have at least similar environmental performance.

Another question that needs to be investigated is whether new nuclear build does offer better lifecycle generation efficiency, i.e. a better conversion rate of primary energy to final produced electricity, than previous designs, and how this efficiency compares to that of a wind farm. This question is of special relevance when viewed in the light of the heightened importance of resource depletion and the general concept of sustainability. Once again, the efficiency of any technology is subject to many parameters and in the case of wind and nuclear, highly specific case- and technology-related parameters (such as wind resource availability and the effects of decreasing uranium ore grade respectively), can significantly affect the performance of the aforementioned technologies. However, it is crucial that the lifecycle generation efficiency is investigated under certain reference conditions, to establish whether the power generation plant in question is a viable option in the first case.

Despite the U.K. Government's apparent support for both technologies, as can be seen in a list of recent publications (BERR 2008b;DTI 2006a;DTI 2007b;DTI 2007c), it has been argued by many that the issue is, in effect, an "either / or" choice. This perception has led proponents of both "camps" to produce rhetoric that, on the one hand promotes the electricity generation technology they support, while at the same time discrediting the other technology. This has resulted in highly polarised debates and positions that have led to the generation of highly conflicting conclusions about the performance, and hence benefits and drawbacks, of each energy supply system. The purpose, of course, of these conclusions has been to influence public and government policy in favour of either wind or nuclear power.

1.5 Research aims and objectives

The main aims of this research are to provide a balanced and comparative assessment of wind power and nuclear power, within the context of Sustainable Development and the U.K.'s efforts to reduce emissions, in a short to medium timeframe. It is hoped therefore, that the results and conclusions of this assessment can contribute to an informed debate on the future implications of using the technologies in question and hence their suitability in tackling the aforementioned environmental issues.

In order to achieve these research aims, a methodology has been devised that combines various existing analytical approaches in such a way, so as to provide a framework for comparing the two energy supply systems, on an equal and fair basis. The work carried out in this thesis is based around the creation of computational simulations for wind and nuclear power, taking into account the whole lifecycle of each technology. The research has been focused on the creation of "case studies" that simulate the performance of current or "near-to-deployment" wind and nuclear technologies. A set of indicators has then been created to assess the performance of the simulated technologies. The aims of this work were guided by concerns relating to the short and medium term impacts resulting from the adoption of each technology, as expressed in the publications of various governmental and international organisations. As such, the indicators created reflect the current understanding of the implications of Climate Change and Sustainable Development. In the interests of transparency, the computer models created for this research are based on information sources that are available in the public domain. Every effort has been made to use the most accurate and complete data sets available, including previous academic works, information from various international organizations as well as reports and data published from relevant industrial sources.

In order to realise the research methodology outlined above, a number of objectives were set:

- To undertake a review of existing literature on the subject. This will include industrial as well as academic sources, as well as any other sources deemed appropriate.
- To define and specify the framework of evaluation. This should include the definition of the temporal and spatial boundaries of the lifecycles under investigation, as well as the identification of all the major processes that feed into those.
- To complete a thorough investigation into the guiding principles of both the wind and nuclear power lifecycles. This will help build an accurate picture of the mechanics of the energy supply systems, therefore aiding the creation of accurate computational models.
- To collate relevant data pertaining to the lifecycles in question. Once this has been accomplished, a critical review of the information is to be conducted in order to identify and resolve gaps and contradictions in the data sets.
- To produce computational representations of the lifecycles under investigations using a "case study" approach to represent short to near-term conditions.
- To define indicators which are considered appropriate to the scope and aims of the research. These indicators will be created so as to assess the technologies in the impact categories that have been highlighted as important by major works in the fields of Climate Change mitigation and Sustainable Development. In order to provide a balanced comparison, certain parameters in each lifecyle will then be varied as part of a parametric analysis in order to identify the possible extreme values for the main indicators under investigation.
- To investigate the computational simulations for a range of input parameters and to use the results for each predefined indicator to then compare the wind and nuclear lifecycles. The implications of these results will then be established, while further implications of each lifecycle will be highlighted.

With the attainment of the above goals, this thesis aims to provide a balanced and contemporary assessment of two of the major energy supply technologies in the U.K. electricity generation industry. This is to be accomplished through the the creation of a range of indicators which will address both historic areas of concern and research (such as energy and emissions –related indicators) as well as for areas of the lifecycles that are seldom commented on, such as land and natural resource depletion. At the same time, a framework for assessing displaced carbon dioxide emissions by each technology will also be investigated. It is thus hoped that the results of this work can then be used in other work of broader scope (techno-economic and/or environmental assessments) or directly useful to policy questions.

1.6 System boundaries, constraints and modeling assumptions

In order to carry out the above steps, it was first necessary to define properly the boundaries of the systems under investigation. From a temporal standpoint, both energy supply systems were assessed based on currently available technologies, as in the case of wind power, or technologies ready for deployment in the near-term (pre-2020), as in the case of the next generation of nuclear reactors. The information gathered was thus either directly related to currently operating facilities or based on expert predictions for the cases where the former was not available. It has been assumed as a result, that the background system remains fairly constant, and that there are no fundamental shifts in the provision of key inputs. An example of the latter would be a shift from fossil fuel based to mostly renewables based energy inputs to the technologies, which could have a profound effect on the results. The current work does not address developments in timeframes longer than those previously stated (i.e. projects implemented post 2020), as this would most likely necessitate a change in the frame of reference used, as well as the assessment of technologies that are currently unavailable (e.g. Generation IV nuclear reactors, novel wind turbine designs etc.).

As indicated previously, the wind and nuclear power cycles were analysed over their whole lifecycle, from material extraction, through to electricity generation and concluding with any necessary disposal stages, at the end of the lifecycle. The energy supply systems are assessed using a functional unit of one unit of energy, in the form of electricity, delivered to end-use. A more detailed explanation is provided in Chapter 3, along with a pictorial representation of the boundaries for each technology. It is important to note that although the energy supply systems themselves are traced from “cradle to grave”, their product i.e. electricity, in only traced as far as its provision to end-use. As a result, any considerations relating to the end uses of electricity are not included within the scope of this work. A graphical representation of the boundary conditions of this study can be seen in Figure 1.4.

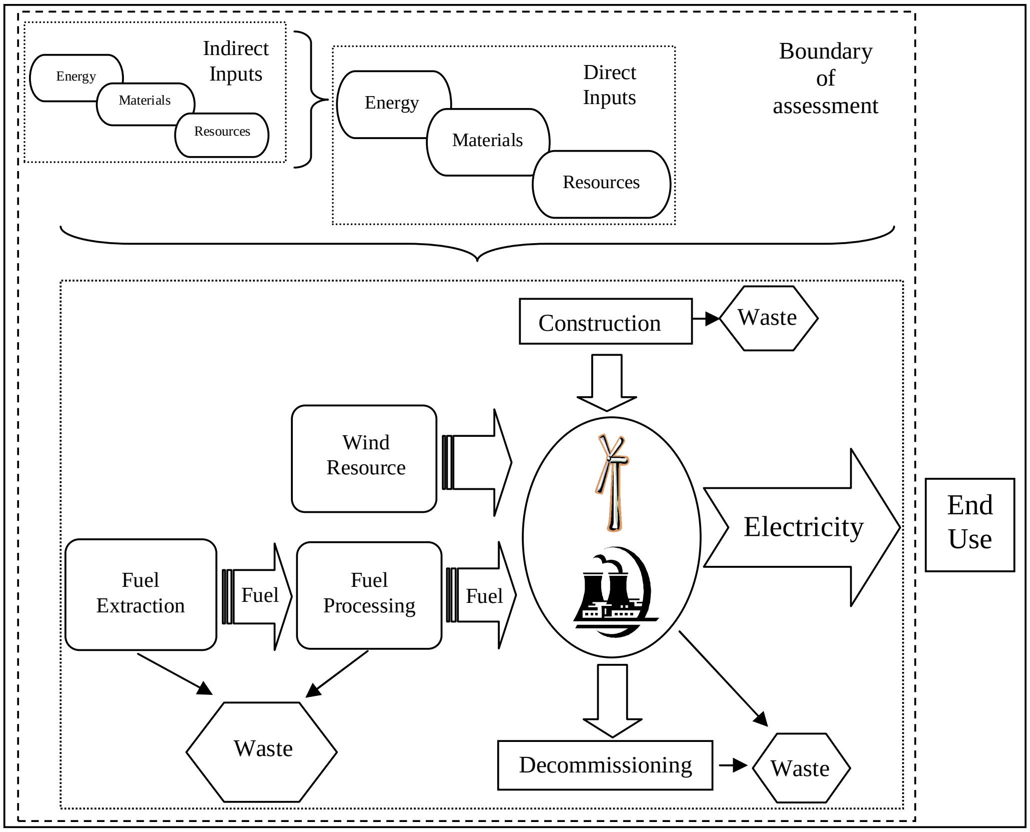


Figure 1.4 Depiction of the boundary conditions of the models in this work

The energy supply systems in question have been assessed with a focus on the U.K. context. This has meant that, where applicable and practicable, the processes have been modelled on real-life conditions and parameters that relate to current or predicted situations in the United Kingdom. Naturally, where processes are undertaken outside the United Kingdom, this has been modelled accordingly. Thus, for example, any material manufactured abroad, has been modelled as such despite the fact that it *could* have been manufactured in the U.K. Similarly, as the models created in this report are meant to simulate real-life conditions as closely as possible, this has meant that although certain processes might be carried out differently *in the future*, and possibly under U.K. conditions, the lack of available data and the inability to predict otherwise, has meant that this was not attempted in this work. A further consideration that also influences the spatial boundaries of the assessment is that of the availability of data. In the cases where insufficient information was available about a process that would normally be carried out in the U.K., it was necessary to substitute this with data adapted from a wider boundary (i.e. the use of inputs to a process from a German context and adapt this to a U.K. one). Similarly, where data for a regional process was unavailable, it was substituted by data pertaining to global conditions.

The computer models created in this work aim to reflect actual facilities and operations as closely as possible. This is a direct result of the use of a “case study” approach. However it is important to note that the models should be considered as “representative” depictions of the real-life systems, rather than an accurate “actual” modelling of the said processes or facilities. The latter would require the expenditure of considerable amounts of effort and the collection of vast amounts of data, putting it beyond the scope of this work. It is also questionable what benefits could be gained from such a detailed analysis, given the uncertainty inherent in projecting current practices into the future or under novel conditions, as has been the case in this work. The fact that the results are "representative" rather than "actual" does not mean however, that the results of this research can be freely transposed to other contexts (i.e. other countries or other timeframes). As the data used in this study is both time and area-specific, it would be difficult to justify the generalisation of the conclusions.

The technologies were assessed on a "stand-alone" basis in a direct comparison. As such, the research presented in the following chapters does not comprise a "systems" analysis, in the sense that it does not seek to investigate the impact of incorporating these energy supply systems into current or future energy sector developments. Hence, it does not constitute a marginal or incremental analysis of the electricity sector, but instead a one-to-one comparison of two technologies that could be incorporated into the electricity generation sector. Naturally, it is not possible to see the technologies as completely independent of the system in which they operate but in the interests of a balanced comparison it is necessary to isolate them, as far as that is feasible. Equally, this work is not concerned with the effects that large-scale deployment of these technologies might have on society at large. It is felt that these types of effects are better investigated by high level systems impact studies, which incorporate economic and behavioural considerations. It is hoped however, that the current work can be used to feed into such studies, by providing an analytical, transparent and detailed analysis of the components of a larger system (i.e. an analysis of the individual generation technologies in the assessment of e.g. the electricity generation sector).

1.7 Data collection and modelling

An important step in the process of assessing the technologies in question was the collection of adequate amounts of data, of sufficient quality. In the interests of transparency, the focus was on the collection of information from publicly available sources, which included academic publications (journals, reports etc), data published directly from relevant industries (i.e. environmental statements, environmental product declarations, sector and government statistics) as well information made public by independent consultancies, pressure groups and non-governmental organisations. In order to model processes in detail, it was further necessary to use both proprietary and open-access international industrial life cycle inventories (computer databases). Once sufficient data was assembled, all sources were checked for accuracy and consistency, through a process of direct comparison and contrast of the data sets and wherever possible, tracing the data back to the prime source. Then, through the combination of these sources, it was possible to build up an accurate and detailed picture of the lifecycles being investigated.

The following step involved correctly defining the processes that were to be modeled and their interconnection throughout their respective lifestyles. As stated previously, a "case study" approach was adopted which was based on the creation of a representative lifecycle using as much real-life site specific data as was feasible. This method was chosen as opposed to a generic assessment approach, where generic, non site-specific facility data would have been used, since it allowed the lifecycles to be tailored to a national context (in this case the United Kingdom), in line with the research aims and scope detailed previously.

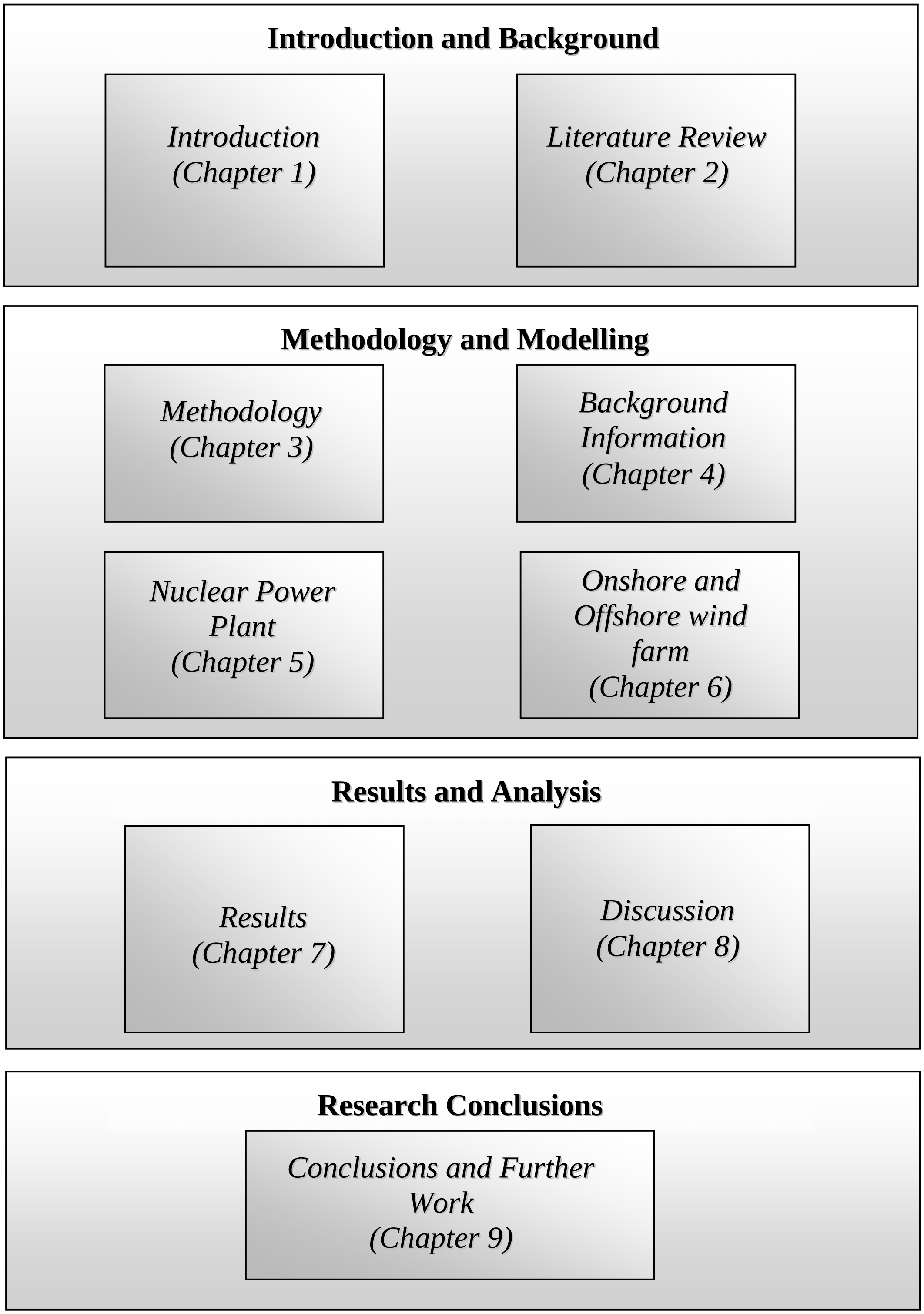
1.8 Definition of assessment indicators

With the above procedures in place, an appropriate assessment framework was defined. This entailed the definition of individual indicators that could address the significance of various impact categories. These impact categories, and hence the indicators themselves, were defined based on the overarching concerns facing the energy sector and society in general, namely how to mitigate against the effects of man-made Climate Change and conform to the requirements of Sustainable Development. The relevant literature in the field was consulted to ascertain exactly which impact areas should be looked at in detail, resulting in a list of indicators, against which wind and nuclear power should be assessed. To further enhance the effectiveness of the research, a parametric analysis of the derived indicators was also undertake, to help illustrate the effect variations in basic input assumptions would have on the lifecycle performance. The variations of parameters were themselves based on current and predicted trends, and provided therefore a range of values for the main indicators, representing possible scenarios for wind and nuclear power.

1.9 Thesis structure

The organisation of this report is such that first the aims, objectives and scope are presented (Chapter 1). Following this, an analysis of the existing literature is presented (Chapter 2), on both the energy supply systems being investigated (wind and nuclear power), and the methodology being applied to this assessment. The methodology is further explained and defined in the following section (Chapter 3), as are the basic modeling assumptions used throughout the research. Background information of each energy supply system is presented in Chapter 4 and a detailed description of the three computer models (onshore wind, offshore wind and the nuclear power plant) created in this work is then provided (Chapters 5 and 6). This is then followed by the presentation of the results of the study (Chapter 7). These results are further examined and the implications of those commented on (Chapter 8), while a summary of the conclusions of the research as well as issues that require further investigation are given in the final part of this report (Chapter 9).

Following the above descriptions, an outline of the structure of this report is presented in Figure 1.5, below:


Introduction and Background
Introduction (Chapter 1)
Literature Review (Chapter 2)
Methodology and Modelling
Methodology (Chapter 3)
Background Information (Chapter 4)
Nuclear Power Plant (Chapter 5)
Onshore and Offshore wind farm (Chapter 6)
Results and Analysis
Results (Chapter 7)
Discussion (Chapter 8)
Research Conclusions
Conclusions and Further Work (Chapter 9)

2. Review of previous energy supply system assessments

2.1 Introduction

This chapter will highlight and critique previous significant contributions to the field of environmental assessment of energy systems. The process of reviewing the existing body of knowledge makes it then possible to identify gaps in the existing literature, which this research subsequently seeks to address. As a first step, the assessment framework used in the work is described; the use of indicators to address different impact categories is detailed and a brief description of the history and the importance of each category is provided, in a global context. The connections between these categories of indicators and the main drivers for change, namely Climate Change and Sustainable Development are also explained. Following this, a review of existing methodologies that can be applied to energy supply system analysis is undertaken, starting first with the general history of these techniques and describing their initial fields of application.

The focus of the chapter then moves on to the particular area of interest of this work, and specifically that of the environmental effects of energy supply systems. Relevant research on the assessment of wind and nuclear power, divided according to the impact category and indicator, is then presented and critiqued thus leading to the identification of areas where further work could be beneficial. It is then these areas that this current work then seeks to address.

2.2 Indicators of Sustainability and Climate Change contributions

In order to assess and compare the different impacts that result from human activities, it is helpful to group these impacts into categories and assign values to them. This, in effect, involves the creation of indicators that reflect the different categories. The use of indicators to assess products and services, as well as whole systems, is well established and promoted by various organisations e.g. by the United Nations in (Millennium Ecosystem Assessment 2005). In a report published by the Nuclear Energy Agency, the use of indicators to assess the progress towards sustainability was deemed to be a useful method, as this allowed for the comparison of different energy sources (NEA & OECD 2001). That report also outlined some general categories that should be considered when assessing the sustainability of an energy system. The major categories suggested there, were chosen as the basis of a framework for the creation of indicators that could be used to assess the technologies under consideration in this work. These categories are:

- Intensity of energy use
- Material flows (per unit of end-product), including those to the environment (e.g. carbon emissions).
- Land use.

Using the above categories as a guideline, the following list of parameters was devised to facilitate the comparison of wind and nuclear power.

1. Direct and indirect energy requirements and efficiency of primary energy utilisation.
2. Greenhouse Gas (GHG) emissions with a special focus on carbon dioxide emissions.
3. Land requirements required to support each life cycle.
4. Material and natural resource requirements (with added focus on water and scarce mineral deposits).
5. Avoided carbon dioxide emissions through the operation of a low(-er) carbon emitting technology.

The fifth indicator is not directly stipulated in the guidelines set out in the NEA documentation, but represents an indication of the contribution of each type of energy supply system in avoiding emissions from the other more polluting electricity generation sources. The analysis of this indicator was considered fundamental from a systems perspective, to the evaluation of the technologies' effect on the climate. Also through its impact on the climate, its impact on the overall sustainability of the system within which, and to which, each technology contributes could also be assessed.

Although this current work is focused on the adoption of wind power and nuclear power in the U.K., any assessment of sustainability, by definition, must be undertaken with a wider context in mind. As such, the focus of this research has been broadened to incorporate impact categories that, although not directly relevant to the U.K., are of fundamental importance in a global context. However, every attempt has been made to ensure that the impact categories defined reflect issues of importance to the U.K. at the time of writing. It is also important to stress that given the wide ranging predictions in respects to the effects of a changing climate, certain indicators may become more relevant to the U.K. with time.

2.2.1 Energy use

As stated in the Introduction, energy use is fundamental to the current status quo of our civilisation and a major contributor to its development. Many researchers and commentators have highlighted the fact that, up until now, development has been based on the use of energy sources that have a high energy output per unit of energy expended by the background support system (the human economy, the Earth's biosphere etc) to make the said energy source accessible, known variably as Energy Gain Ratio or Energy Return on Investment amongst other terms used (see (Cleveland 2006;Gagnon 2008;Roberts 2006;Smil 2006);the exact definition used in this work is presented in Section 3.5.1.6). . These energy sources have been mainly in the form of fossil fuels, but as these will eventually be depleted and society will have to rely on alternatives including wind and nuclear, the importance of the Energy Gain Ratio will become more pronounced. The use of this indicator has been cited as an important aspect in the comparison of different energy supply systems (WEC 2004).

2.2.2 Greenhouse gases

The importance of the GHG emissions impact category, and the resulting indicator, has in effect already been described in the introductory section on Climate Change (Section 1.2). As such, only a brief description of its importance is given here.

As stressed previously, the emission of greenhouse gases, and carbon dioxide in particular, have been intrinsically associated with the effects of Climate Change.

Hence, there is an ever increasing importance placed on the choice of energy supply systems that have the lowest associated emissions. The calculation and aggregation of these emissions however, must be carried out over the whole lifecycle of the system being examined. This is important as certain technologies produce little or no emissions at the point of electricity production but might have significant emissions associated with other parts of their lifecycle. Thus, any energy supply system that has lower emissions than an alternative, all else being equal, is likely to be seen as a more sustainable and thus appropriate choice, given current concerns.

2.2.3 Land use

Since humanity's transition from the "hunter-gatherer" to a more agrarian society, its activities have transformed large proportions of the Earth's surface. This has either been effected through the conversion of natural landscapes for human use or through a changing of land management practices on land already dominated by human activities. Examples of this include the clearing of forests and scrub land for agriculture or for housing and the intensifying of production methods on farmlands. Although a wide variety of methods of land use management are employed around the globe, their end result is generally the same: the acquisition of natural resources in order to satisfy human needs. This is usually accomplished at the expense of the natural environment (Foley & et al 2005). In their Synthesis report, the Millenium Ecosystem Assessment Board concluded that "*the structure of the world's ecosystems changed more rapidly in the second half of the twentieth century than at any time in recorded human history, and virtually all of Earth's ecosystems have now been significantly transformed through human actions*" (Millennium Ecosystem Assessment 2005).

The issue of land requirements and its utilisation is slowly rising in importance in the discussion of environmental impacts of power generation. This is especially true with respect to renewable power. Given the increasing demands and pressures on the ecosystem, it is becoming increasingly important to develop and adopt technologies which are designed to maximise the efficiency of resource use, among which resources is land. As a result of the debate concerning the land requirements of renewables, the amount of land sequestered by them to produce a product, in this case electricity, may become an influencing factor in the level of their uptake by society. Certain commentators have made a point of highlighting the low "energy density", i.e. the amount of energy for a given land take, of wind and renewables in general both in a UK and a US context (Fells 2002;Pimentel et al. 1994). As such, it has been argued that although renewable energy technologies can have lower environmental impacts in general, they require more land than conventional fossil fuel generators and therefore might find themselves competing with other essential land uses, such as housing, agriculture and forestry. Nuclear power similarly has been targeted on this issue, mainly because of the land disturbed by the uranium mining operations and the land sequestered for the storage of nuclear waste.

2.2.4 Material requirements/Natural resource depletion

In this work, two different investigations are carried out with relation to resource depletion. The first involves the assessment of the material (building) requirements, used directly by the construction of each energy supply system. It represents an indication of the drain each system has on the supply and demand of commonly used construction materials. It should be noted that the focus in this first investigation is on the materials in an aggregated form (e.g. concrete) and not to the minerals from which they originate (e.g. sand, limestone etc).

Currently, the consumption of construction material resources is not a pivotal issue, as no fundamental lack of reserves for any one material has yet been observed. However, the current and expected growth rates for relevant sectors in certain parts of the world (mainly Asia) have already placed a strain on the supply of certain materials such as steel (Aubrey 2007). The consumption of basic construction materials can be linked to a depletion of the world's mineral resources, so an increase in one leads inevitably to an increase in the other. Given that the exploitation of mineral resources generally consist of energy-intensive production processes, energy supply systems with large material requirements will also have larger energy-related impacts. Specifically with regards to the systems under investigation here, the material requirements of both wind and nuclear have both been brought into question, as will be seen in subsequent sections.

The second investigation utilises a whole lifecycle perspective, and involves the quantification of the mineral requirements for each energy supply system. This second investigation is more in-line with the concept of Sustainability as it provides a clearer depiction of the effect that each technology (wind and nuclear) has on the environment. Appropriate mineral resources that should be investigated for energy systems has generally been laid out in work such as (Karen Leffland & European Environment Agency 1997).

2.2.4.1 Water

An important category included under the title of resource requirements/depletion, that deserves special attention is the water requirements of different energy supply systems. One of the most underreported indicators in electricity production is that of the water usage. Water is considered of paramount importance for biological production and therefore its inclusion as an indicator for Sustainability is fundamental. Historically, water has been considered a non depletable natural resource, and as such the amount of water used to facilitate certain processes has never been properly valued. The value of water however is also hard to assess and depends on the delineation of what is included in its value. Although water contributes to a complex system of services and resources, each of which has an economic benefit, defining the aggregated benefit and thus its value is difficult. The true importance of water is only realised when there is a shortage of it.

Water crises are evident around the world in both developed and developing countries. However, most crises are not related to the scarcity of water per se, but rather to the ineffective management of the resources in the first place (Wilkie 2007). Thus good water governance is crucial in meeting the aims of sustainability both on a regional and global scale. The protection of water supplies as a natural resource has been the focus on many United Nations agencies (UNESCO & UN 2006) and has been highlighted as an issue of special importance by the IPCC in their reports on Climate Change (Kundzewicz 2007). With regards to energy supply systems, the water requirements of the different technologies can potentially affect their adoption, especially in areas and during times that water scarcity is a major consideration.

2.2.5 Avoided emissions

An important addition to the impact category of GHG emissions is the concept of “avoided emissions”. As both renewables and nuclear power are considered to have lower carbon emissions than conventional fossil fuel-fired generation, it is maintained that if the former displace the electricity produced by conventional generation, then they will also displace the emissions that would have been produced. This is possible in the U.K., because electricity from renewables is given priority access to the Grid (under the Renewables Obligation) (DTI 2006b), while nuclear always runs as “baseload”, and therefore provides electricity that would otherwise have to be provided by other conventional baseloading plants, such as large gas-fired or coal-fired plants. The specific types of fossil fuel-fired power units that will be displaced by wind or nuclear generation, however, vary with a variety factors, including the time of day, month and year as well as the relative prices of fuels used in generation. The quantities of emissions displaced also vary with the age of the fossil fuel-fired units, as well as their relative levels of efficiency and pollution control. Thus, the emissions from displaced electricity depend on the dynamic interaction of the electrical grid, the emission characteristics of the connected electricity generators, the loads on the system and market forces, as well as a variety of regulatory factors.

2.2.6 Summary of indicators

It should be noted that while an aggregated indicator would make the comparison of impacts between different systems easier, it is difficult to assign weightings to categories that have no financial markets, and therefore no *assigned* value whether economic or otherwise. These categories include natural assets like clean air and water, ecosystems such as wetlands, coastal zones, rainforests, mountains, and deserts. It is obvious that these assets do have an intrinsic significance but it is nearly impossible to actually apply a consensus value, since this will vary depending on temporal and spatial factors, as well as on the person or collection of people assessing it. On the other hand, working with a range of indicators has advantages, as it provides the opportunity to create detailed indicators that reflect more precisely the characteristics of the different impact categories to which they relate. This then also allows for the weighting of the indicators, at a subsequent stage of analysis according to the requisites of different assessments.

The indicators chosen in this work reflect current concerns and are, of necessity, limited in their temporal and spatial scope. While it is possible to create a large number of indicators to cover a wide range of impact categories, such an approach is beyond the scope of the current work. The scope has been purposefully limited in order to provide as detailed a picture as possible of the complications that are inherent in each technology being investigated.

The use of indicators to assess energy systems can be seen in other works such as (Afgan & Carvalho 2002;Afgan, Carvalho, & Hovanov 2000;Evans, Strezov, & Evans 2009;Vera & Langlois 2007). However, each report uses its own definitions and boundary conditions so it is hard to provide a comparative analysis of previous work. Thus, it is important to remember that comparisons between previous works or between this work and previous work are best undertaken qualitatively.

2.3 Literature review of assessment methodologies

In order to assess the aforementioned indicators and their respective categories, various methodologies have been devised. As no single methodology covers all the parameters being investigated in this research, it has been necessary to combine various aspects from the different approaches into a coherent framework of assessment. The following section is divided by a methodological approach and in each category previous important research is presented.

2.3.1 Energy Analysis (EA)

Energy analysis is a method for calculating the total amount of energy required to provide a good or a service (Mortimer 1991). The method was first developed in the 1920s and '30s but the biggest body of research was undertaken mainly in the 1960s and '70s, especially after the "oil shocks" in 1973 and 1974. As a result of that, research topics from that period were permeated by concerns about energy resource depletion and scarcity.

Certain sources trace the origins of Energy Analysis as far back as the period between the First and Second World Wars, when the failure of the financial system to enable the exploitation of unused resources by the, then-unemployed, workforce led the Nobel Prize winner Sir Frederick Soddy to suggest energy could provide a more fundamental unit of accounting than money. His ideas were not well received at the time and the use of Energy Analysis remained largely dormant until it came to prominence in the 1970s (IAEA 1994). The impetus for the revival came from a growing skepticism about the effectiveness of conventional economic theories and the realisation that attempts at continual growth were subject to the availability and exploitability of the world's finite resources (Klimes 1974). It is unclear who exactly was responsible for the resurgence of Energy Analysis, but Howard Odum is attributed this role through the publication of his 1971 book "Power, environment and society", in which he proposed that money and energy flow along the same paths but in opposite directions (Odum 1971). Around the same time, work was being carried out at Oak Ridge National Laboratory, with Hirst and Herendeen being the most prominent proponents at the time (Klimes 1974). Odum's work also stimulated a number of other researchers, among them Leach, Pimental and Slesser to examine the costs of various commodities including food production (International Federation of Institutes for Advanced Study & IFIAS 1974; Slesser 1978; Slesser & Hounan 1979; (Leach 1973;Leach 1975b), while researchers at the Energy Research Group of the Open University, namely Chapman et al, extended the use of the methodology to illustrate the energy requirements of copper and aluminium production (Chapman et al 1975) and most notably, the then budding nuclear power industry (Chapman 1975a;Chapman & Mortimer 1974;Chapman 1974b;Chapman 1975b). Other papers were also published, focusing on the energy requirements of manufactured materials e.g. (Hannon 1972), with the emphasis shifting towards the assessment of industrial processes (Boustead & Hancock 1979), towards the end of the decade. At around the same time, it also became apparent that the methodology could be used to inform and evaluate large scale projects and policies (White 1998). From that point on, the methodology progressively grew into a tool for assessing complex systems, from engineering designs to biological systems (Hammond 2007b), and that allowed a detailed analysis of the inputs and outputs of system.

As could be expected with most developing disciplines, Energy Analysis soon fell prey to ambiguities in both methodology and interpretation. The first attempt at creating a common basis for all works of Energy Analysis was made at a workshop organized by the International Federation of the Institutes for Advanced Study (IFIAS) in Sweden during August 1974. The IFIAS workshop developed a set of guidelines for the use of energy analysis, by defining the conventions and methodologies to be used in such works (International Federation of Institutes for Advanced Study & IFIAS 1974). A second conference in Stockholm in June 1975 had as its main aim, the definition of the interface between Energy Analysis and Economics, in particular the role of energy analysis in technology evaluation, the comparison of energy and economic efficiency and integration of physical information into economic behavioral relationships. It is important to note however, that since these original guidelines, many conventions were changed as a result of the need to emphasize different aims and objectives, leading not only to an ever evolving field of work, but also opening up Energy Analysis to the criticism of lacking a sound basis of evaluation.

2.3.2 Net Energy Analysis (NEA)

Within Energy Analysis, the most acute controversy was centered on the area of Net Energy Analysis (NEA), i.e. the energy costs of producing energy. NEA compares the energy required for all inputs in developing a new energy technology (energy itself, materials and services) with the energy that the technology will eventually produce (Herendeen 1988). In particular, the aims of NEA originally reflected the suspicion that certain technologies could result in being “net energy consumers” rather than producers.

One of the first attempts to standardise the methodology of Net Energy Analysis, was introduced in the mid-1970s with the establishment of the Institute for Energy Analysis in Oak Ridge, Tennessee and the Energy Research Group at the Open University in the UK. Both groups published reports, documenting and setting outlines for “good practise” in the growing field of Net Energy Analysis, for example (Perry A.M, Devine W.D, & Reister 1977), (Chapman 1974a), (Hill 1975), (Bullard C.W., Penner P.S., & Pilati D.A. 1978) and (Mortimer 1991), and thus helped establish the methodology as an important contributor to public debate on the feasibility and, as it would be later come to be known, sustainability of systems and products.

In many ways, the original conventions of Net Energy Analysis reflected the issues of the time, which were related to concerns about the depletion of mineral and fossil fuel reserves. These concerns led to proposals to instigate the use of, at the time, “unconventional” sources of energy, such as nuclear power, and to develop new energy sources encompassing mainly what are now generally known as renewables. In many cases, since the conventional economic evaluation of these new technologies showed them to be more expensive than conventional source of energy, they were deemed to be inadequate solutions. However, standard methods of analysis were increasingly being seen as unreliable and incomplete, since they did not take into account the uncertainty of price fluctuations in the future. It was believed however, that Energy Analysis (and as a result Net Energy Analysis) offered the solution to this problem, as it was based solely on physical properties. This meant that, unlike economic measurements which were prone to erratic fluctuations resulting from the unpredictable behaviour of the market, the measurements of Net Energy Analysis were grounded in physical reality. NEA provided a means of directly comparing the energy output of a technology with the energy required to create it. It was believed that such an assessment provided the ultimate test for any new technology. If it consumed more energy than it produced (hence had a negative net energy value), it could not provide any useful contribution to energy supplies and would be dismissed as a “net energy sink”. Conversely, if the opposite were true i.e. it produced more energy than it consumed, then the technology should be adopted even if its economic evaluation was found to be unfavourable. This partly explains the emphasis on the concept of Primary Energy in Net Energy Analysis, which was based on the use of calorific values to measure quantities of energy, since this allowed the aggregation of energy from different sources, thereby disregarding other differences between the fuels (Mortimer 1991).

The main objections to NEA were related to the conventions used in thermodynamic terms and over what inputs should be counted as going in to the production of energy, therefore intrinsically questioning the conventions about the boundary conditions assumed. As such, these objections attacked the notion that the economic and human life-support system could be separated into the “energy system” and the “remainder” and that studying the “energy system” in isolation was valid (Herendeen 1988). Questions were also raised about the methodology’s usefulness and whether its aims could be addressed more quickly using other methods. It would be fair to say then, that the main critics of Net Energy Analysis, were economists, who suspected that energy analysts were promoting a so-called “energy theory of value”, thereby replacing Economics as the preferred method of evaluating and prioritising social and industrial activities. Since these initial concerns were raised however, it has been generally agreed that Net Energy Analysis has no role as a normative discipline, but should be used more as a descriptive tool to provide insights into processes rather than try to evaluate them.

A more pragmatic conclusion would be, however, that Net Energy Analysis cannot be taken as an absolute measure of a technology’s viability in all circumstances. What it can do is provide results that can be used comparatively. The basis of NEA methodology requires the collection of data about the system under examination and calculation and comparison of energy flows within the assessed boundary conditions. Various methods can be used in Net Energy Analysis to carry out this collection and comparison of energy flows, with the most prominent methods being Process Analysis (PA), Input/Output Analysis (I/O) or a combination of both.

2.3.2.1 Process Analysis (PA)

Process Analysis involves “the tracing of the energy inputs to all the products and services on which a process depends, described principally in physical terms” (Mortimer 1991). Process Analysis is considered, a “bottom-up” approach that requires the definition of specific processes involved in a system or the production of a product, the analysis of each step in the life cycle individually and subsequently the summing up of the energy expended for, and the outputs coming from, each process. The origins of this method can be traced back to the works of Chapman (Chapman 1974a) and Boustead (Boustead & Hancock 1979), though the method has probably been around much longer without having been categorised as such (ISA 2006). The PA approach is best suited to analysing specific processes where material and energy flows are well documented and is considered more flexible than other methods (such as the I/O method described next), as it allows a modular approach and the optimisation of individual processes in the life cycle. On the negative side however, Process Analysis can carry significant systematic errors due to the truncation of system boundaries, which in turn are related to the difficulty of defining appropriate subsystems (ISA 2006). PA can produce potentially very accurate, reliable and specific results. However, to achieve this, it is necessary to investigate in detail the energy used in each of the processes, which are themselves progressively further removed from the actual system being investigated.

2.3.2.2 Input-Output Analysis (I/O)

Input-Output Analysis was originally developed for Economics by Wassily Leontief in 1936. The method is based on a matrix which links the flow of money and products from one sector of the economy to another. The I/O approach was developed into a tool for Energy Analysis in 1973 by R.A. Herendeen, from the Centre for Advanced Computation at the University of Illinois. The original model divided the U.S. economy into 43 economic sectors, measuring the flow of products and cash flow between sectors. Herendeen’s method linked energy flows to the already existing product flows and was designed in effect, to express product flows in terms of energy instead of monetary units (White 1998). The main advantage of the I/O method when applied to Net Energy Analysis is that it links data that is readily available in economic terms, to its equivalent energy units providing a thorough analysis of all product flows. However, as it is dependent on highly aggregated data (i.e. industries as a whole), and based as it is on a statistical “top-down” approach, it cannot take into account different methods of production, or products that do not fall into the typical products of a sector (for example a nuclear power plant as a product of the construction sector). Also, errors can occur if products are liable to large price fluctuations while the energy costs do not vary accordingly. Although the methods of statistical energy analysis (such as I/O) can be used in conjunction with those of Process Analysis, the latter is preferred as a means of obtaining results for specific processes (Mortimer 1991).

2.3.2.3 Hybrid Analysis

It is generally accepted criticism that I/O analysis tends to overestimate energy intensities because of the inability to separate product costs from auxiliary services (e.g. bank interest, profit margins, insurance costs etc.), while PA has the tendency to underestimate energy requirements and environmental impacts, since it does not include “second-order” energy inputs associated with individual processes (White & Kulcinski 2000). As this became increasingly apparent, several hybrid techniques were developed (e.g. Bullard et al (Bullard C.W., Penner P.S., & Pilati D.A. 1978) as cited in (ISA 2006)) that attempted to combine the advantages of the two aforementioned methodologies, namely completeness on the one hand and level of detail on the other, while avoiding the drawbacks inherent in the original methodologies. This method however, is highly complex as it is necessary to make sure that the boundary conditions used by each one of the two combined methodologies match. Furthermore, with the use of ever more detailed Process Analysis databases, this hybrid approach has become less necessary.

2.3.3 Life Cycle Assessment (LCA)

"Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment…[]"

SETAC (SETAC 1993)

The European Standard ISO 14040 defines Life Cycle Assessment (LCA) as: '... a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system' (ISO 1997).

The origins of Life Cycle Assessment can be traced back to the same period as that of the development of Energy Analysis, i.e. the early 1970s. In fact, it has been pointed out that in the first decades of their development and implementation, the methodologies were in effect, the same. At that time, the modelling aims of LCA focused mainly on the use of energy and the production of final waste, therefore providing a close link with Energy Analysis. LCA was thus, in effect, being used to calculate the so-called ‘‘embodied energy’’ of a product. Objects of analysis were mainly household products (Udo de Haes & Heijungs 2007). However, the additional need from the 1980s onwards, to assess not only the energy requirements of processes, but also their resulting environmental impacts, led to the further development of LCA as a methodological tool in its own right.

Work carried out by Boustead and Hancock (Boustead & Hancock 1979) as well as Franklin and Hunt (as quoted in (Boustead & Boyd 1996)) set the basis for the further development of the field of "environmental accounting", as Life Cycle Assessment was originally known. One of the first attempts to set out official guidelines for Life Cycle Assessments was conducted by the Society of Environmental Toxicology And Chemistry (SETAC) in the early 1990s (SETAC 1993). These guidelines later influenced and were used in studies of the life cycle impacts of various products as well as energy generating systems, as can be seen in the ExternE projects of the European Commission (CEC & ETSU 1995), work by the International Atomic Energy Agency (IAEA 1994;IAEA 1996) and others. The original guidelines set up by SETAC were subsequently codified by the International Organisation for Standardisation (ISO) (ISO 1997) and are revised at regular intervals, with the latest addition being (ISO 2006). From the end of the nineties, a third organisation influenced the development of LCA; the United Nations Environment Programme. In 2002, this organisation started a co-operation with SETAC in the so-called UNEP/SETAC Life-Cycle Initiative, the main of which was to bring LCA and other life-cycle approaches into practice by stakeholders in developing countries.

Work on the theory and application of LCA, according to the precepts of Sustainable Development, have been undertaken by various research groups and analysts such as (Dones & Heck 2006;Frischknecht, Jungbluth, & et al 2007;Frischknecht & Rebitzer 2005;Pennington et al. 2004;Rebitzer et al. 2004;Weidema et al. 2004), as well as by industry in the form of "Eco-labelling" of products, and more relevantly to this current work, Environmental Product Declarations, which are described in following sections.

Life Cycle Assessment is a “cradle-to-grave” methodology, meaning that its purpose is to systematically analyse a product from the stage of raw material extraction, through its use, to its final disposal. In recent years, “lifecycle thinking” has become ever more crucial, with the increasing emphasis placed on the concept of “Sustainable Development”. It has become an important tool in informing environmental policy making and is now commonly used for the communication of environmental performance results, for example in the form of Environmental Product Declarations (EPD). Life Cycle Assessment however, as all methodologies that aim to simulate real-world systems, has its limitations. The main drawbacks of LCA are the large quantity of high level data required to produce valid results, as well as issues concerning the boundary conditions of each study; the static nature of the analysis also is seen as a limitation of the applicability of the methodology (Ayres 1995;Rebitzer, Ekvall, Frischknecht, Hunkeler, Norris, Rydberg, Schmidt, Suh, Weidema, & Pennington 2004). Other issues relating specifically to energy systems, cannot also be fully addressed with LCA, such as hydropower’s impact on land use or nuclear power’s unlikely, but potentially catastrophic, impacts in the case of a failure(Udo de Haes & Heijungs 2007).

2.3.3.1 Environmental Product Declarations (EPD)

An Environmental Product Declaration is defined as “quantified environmental data for a product with pre-set categories of parameters based on the ISO 14040 series of standards, but not excluding additional environmental information” (GEDnet 2008).

The overall goals of an EPD are to communicate verifiable and accurate information on the environmental aspects of goods and services. To achieve this end, one of the main aims of EPDs is to provide the basis for a fair comparison of the environmental performance of products. EPDs have recently been implemented in industry, and their use has been extended to electricity generation as can be seen in their use by large European utilities, such as Vattenfall in Sweden (Vattenfall AB 2003;Vattenfall AB 2004b;Vattenfall AB Generation Nordic Countries. 2004), British Energy in the U.K. (AEA Technology & British Energy 2005) and ENEL in Italy (Enel SpA 2004).

Environmental Product Declarations however, have the drawback of being difficult to interpret, while their focus is on providing data for certain predefined impact categories, rather than more generally for assessing the sustainability of the product/service (Steen et al. 2008). As such, the methodology was not deemed compatible with the scope of this research and not adopted.

2.3.4 Other methodologies

Apart from the methodologies described above, a multitude of other approaches have been used to assess energy supply systems. Most of these methodologies aim specifically to assess certain predetermined aspects and therefore were not considered relevant to the scope of this current work. One methodology of relevance to this current work is Exergy Analysis which is described in the following section.

2.3.4.1 Exergy Analysis

Another method that has been used to assess the various industrial processes including the generation of electricity, from a variety of sources, is Exergy Analysis. The exergy of a thermodynamic system can be defined as “the maximum theoretical useful work […] obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment, while the system interacts with this environment only.” (Tsatsaronis 2007)

Exergy analysis can be employed to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of a process. It can, therefore, indicate the possibilities of thermodynamic improvement of the process under consideration (Hepbasli 2008). Exergy analysis has been applied to both energy supply systems, including wind and nuclear power plants, as can be seen in the works of Ozegener, Hepbasli, Dunbar, Rosen, Koroneos and others (Sahin, Dincer & Rosen 2006; Dunbar, Moody, & Lior 1995; Durmayaz & Yavuz 2001; Hepbasli; Koroneos, Spachos, & Moussiopoulos 2003; Kotas 1980; Ozgener & Ozgener; Rosen & Dincer 2003). Exergy analysis has also been applied to national economies and whole systems, as illustrated by the research of Wall, Rosen, Hammond and others (Hermann 2006; Nakicenovic et al, 1996; Hammond, 2001; Haldi and Favrat, 2006; Wall, 1987; Wall, 1990).

Exergy analysis however was deemed beyond the scope of this current work. Whereas exergy analysis has advantages for the evaluation of thermodynamic systems, it has been argued that the link between such environmental aspects as resource utilisation, pollutant emissions, and exergy is only indirect and therefore provides insufficient basis for environmental appraisal (Hammond 2004).

2.4 Literature Review of assessment of energy systems

The studies reviewed in the following sections, have been split according to the indicator they relate to. In some cases, however, previous research will have included indicators that relate to more than one impact category used in the current research (especially in the case of LCAs). In these cases, these works are highlighted again in the relevant sections of this review, but only commented on where necessary. It is important to note at the outset of this literature review that the comparison of different studies is difficult, as the results are highly dependent on the boundary conditions used in the different studies (which are not always explicitly stated) and the spatial location of both the power plant and its supply chain (WEC 2004). As such, the results may not be directly comparable or even directly relevant but, as it would be impossible to re-adjust the conditions in all previous studies to provide a uniform starting point, the emphasis when comparing other work should be on the qualitative rather than quantitative aspects. The literature review in this thesis has been confined to previous works that encompass at least one of the technologies considered in this current work (wind power or nuclear power, or both). Research covering other power plants (such as e.g. (Hill & Mortimer 1996)) although useful as a cross-reference, was deemed thus beyond the scope of this report.

2.4.1 Energy and GHG Emissions

As mentioned previously, the interest in analysing power generation technologies, in terms of energy, can be traced back to the 1970s and 1980s, when concerns about the depletion of fossil fuel reserves and the dependence of western countries on the fuel supplies from the Middle East (especially after the oil embargoes in the 1970s), led many governments to seek alternatives sources for energy. Many studies on a variety of power generation technologies have since been published.

2.4.1.1 General studies on the electricity generation

Studies contrasting different technologies, can be found as far back as 1974, when Chapman questioned the "*energy benefit*" of nuclear power (Chapman & Mortimer 1974), but have since encompassed most generating technologies. As in the case of Chapman, most research was originally focussed on the energetic evaluation of different power sources. However, with the increased awareness of the Greenhouse effect and then the phenomenon of Global Warming in general, the focus started to shift towards the evaluation of GHG emissions, as well as other local and global impacts.

From an international perspective, work on both the energetic and environmental impacts of electricity generating technologies has been carried out by both academic and governmental organisations. One of the largest studies into the environmental effects of electricity generation was carried out in the ExternE project by the European Commission (CEC, EEE, UK, & ENCO 1995;CEC & CEPN 1995). The focus of the work however was mainly on the evaluation of the monetary costs from the lifecycle externalities, and therefore contained only limited information about the emissions and energy requirements for the different technologies considered. Proops et al (Proops et al. 1996) provided an analysis of the emissions from electricity generation for the U.K. based on I/O analysis on a whole-lifecycle basis. The work was amongst the first to present an analytical breakdown of emissions by life cycle stage for a range of technologies. However, the work then presented the emissions savings compared to older coal-fired power plants, making the results harder to interpret and use in a comparison with other work. Although the work was extensive, it was based on data from 1996, while also suffering from the drawbacks of I/O analysis, stated previously in the methodology review.

Studies on electricity generation technologies also include works using more than one method of evaluation (i.e. Input/Output Analysis together with Process Analysis). Friedrich (Friedrich & Marheineke 1994) used a hybrid approach to assess 6 technologies. The analysis showed that nuclear and wind had almost identical emissions over their lifecycle. The work also concluded that backup should be added to renewables to account for their variability, while the results could have no general validity as they were time and site-specific. Voorspools (Voorspools, Brouwers, & D'haeseleer 2000), also provides a useful analysis of wind, nuclear and PV using a LCA approach based on Process and I/O analysis. The report also highlighted the different limitations of each methodology, illustrating that the I/O method usually results in the calculation of higher emissions compared to PA. The results showed that nuclear performed marginally better than wind with respect to both emissions and energy gain ratios. However the work was undertaken for Belgian conditions, using older datasets.

In the mid-nineties, the IAEA held a workshop to summarise work on GHG emissions from energy systems, in the hope of providing information for policy makers (IAEA 1996). However, as the work was intended to provide a useful summary rather than a in depth analysis, the boundary conditions were not standardised. One of the works included in the proceedings was that by Van de Vate (Van De Vate 1996a) who was among the first to aggregate different emissions species (i.e. CO_2, CH_4, SO_2) using their *global warming potentials* as they were then defined (global warming potentials are the factor by which the quantities of each gas species need to be multiplied, in order to be become equivalent to some other baseline gas, usually carbon dioxide, and therefore addable). He also attempted to associate the energetic results of older studies with their equivalent GHG emissions, using the embodied carbon of materials (van de Vate 1997). While the research concluded that nuclear power performed better than wind with respect to GHG emissions, it also concluded that there were few pieces of work covering all technologies available and that a consensus of evaluation techniques was a prerequisite of effective policy guidance.

White and Kulcinski (White & Kulcinski 2000), based on the doctoral thesis of the former (White 1998), provided results for emissions and energetic indicators for a range of technologies, including fusion reactors, based on materials extracted from lunar exploration. The work provided a consideration of the whole lifecycle and stressed the importance that Front and Back End emissions had on the nuclear and wind power lifecycles therefore pointing out that they could not be considered zero-carbon technologies. However, the analysis was based on old datasets and results from statistical and I/O analyses, making it generic and broad, and therefore suffered from many of the shortcomings already highlighted in previous works.

More recently, reports focusing on the “cradle-to-grave” approach inherent to LCA have become more widespread, of which studies by (Michaelis P. 1998) who assessed the lifecycle impacts of different power plants for the Royal Commission on environmental pollution report (Royal Commission on Environmental Pollution 2000) and (Hondo 2005;Nomura et al. 2001) in Japan, are representative. Gagnon et al (Gagnon, Belanger, & Uchiyama 2002), provide an LCA overview of hydro, nuclear and wind power, with useful discussions on their other impacts (such as land-use; see following sections). However, their report contained very little information about the sources of the data and the manipulations it underwent, making therefore any comparisons with other research, at best, questionable. However, the implicit assumption is that the results are based on and related to Canadian conditions. The work of Sims et al (Sims, Rogner, & Gregory 2003) provided ranges of greenhouse gas (GHG) emissions for different technologies. However as the purpose of the research was to calculate the GHG mitigation costs for different technologies, the main focus of the work was on costs while the emission estimates were taken from other studies, with little data provided on the calculations.

In July 2004, the World Energy Council published a report (WEC 2004) comparing energy systems using an LCA approach and focusing on three main end uses; electricity, space heating and transportation. The work concluded that nuclear and wind had the lowest emissions per kWh produced, placing nuclear emissions lower than wind. The studies included however were limited to those from WEC members that had been published within a 10-15 year timeframe from the time of the report. The WEC report in effect contained many of the previously mentioned pieces of research.

A thorough literature review for all major energy supply technologies was carried out by (Weisser 2007), focusing mainly on the emissions using a LCA methodology. The report was based on previous work carried out by the IAEA and provided a useful overview of current results, focusing its review mostly on recent publications. The results showed once again that nuclear and renewables had the lowest associated emissions, while also showing that wind had the higher emissions. However, the report noted that no particular effort was made to ensure that all the results taken from the different studies had consistent boundaries. It also noted that results based on a LCA were highly site specific, making them more an overview rather than a generically applicable guideline. Spadaro et al (Spadaro, Lucille Langlois, & Bruce Hamilton 2000) was one of the main contributors to the above report and in many ways provide the conclusions previously cited.

A body of work that is of direct relevance to this current research, is that from a group of researchers from the Paul Scherrer Institut (PSI). Publications such as (Burger B. & Bauer C 2007;Dones R. 2003;Dones et al. 2007;Dones et al. 2005;Jungbluth et al. 2004) provide a useful point of comparison with current work as they are based on a similar dataset, therefore providing a common point of reference. However, most of that work was geographically biased as it was defined mainly for Swiss conditions and therefore not directly applicable to conditions in the United Kingdom. The work shows that wind and nuclear have amongst the lowest GHG emissions, with a marginal difference in favour of nuclear when compared to wind. In 2006, the Parliamentary Office of Science and Technology published a note on the emissions from a wide variety of electricity generation technologies, based on a LCA methodology (Parliamentary Office of Science and Technology 2006). The work in effect concluded that renewables and nuclear power had the lowest CO_2 equivalent emissions of the technologies considered, but stating that the emissions from wind (both onshore and offshore) were almost identical to those from nuclear emissions. However, no information regarding the assumptions behind those results was provided in that report. Most recently, Varun et al (Varun, Bhat, & Prakash 2009) reviewed many of the current and previously mentioned studies and concluded that renewables (and among them wind) had the lowest associated GHG emissions. However, the carbon dioxide emissions given had a range of two orders of magnitude, while the results for nuclear power were on the higher end of those previously considered.

The above section has sought to provide a concise overview of previous pieces of research which are of relevance both to wind and nuclear power, as well as to other electricity generating technologies. However, as this study is focused specifically on the comparison of wind and nuclear power, studies of direct relevance to those energy supply systems are described in the following sections separately.

2.4.1.2 Wind power related studies

There have been many studies on wind power, both in the form of single technology investigations and as well as part of a wider set of electricity generation options.

As part of the IAEA research review, van de Vate reviewed the then available literature which was based mostly around small scale wind turbines (under 500kW), and concluded that emissions from wind power had a large range of values (ranging from 18 - 123 gCO_2eq/kWh) (van de Vate, J.F, 1994). He also noted that there was little consensus on accounting methodologies and boundary conditions or as to whether storage or backup should be considered a necessity. Hartmann (Hartmann 1996) also conducted work into the related emissions of wind and solar power, concluding that wind had emissions of approximately 20 gCO_2eq/kWh. His research also undertook one of the first system integration studies for the calculation of avoided emissions commenting that wind power could displace almost all the emissions from a coal-fired power plant through the substitution of electricity generation.

Among the first major studies to be published on wind turbine energy analyses, were the studies by Uchiyama (as cited in (IAEA 1994)) which looked at various energy parameters, and the work by the European Commission (CEC, EEE, UK, & ENCO 1995) which concentrated, however, specifically on the economic evaluation of the externalities associated with wind power. Later, Uchiyama (Uchiyama 1996) also looked at the net energy and associated GHG emissions with wind and solar technologies for Japanese conditions. The report also concluded that nuclear produced much lower carbon than conventional fossil fuel generation but that the energy payback times of wind and solar were much lower than those of the nuclear power.

Grum-Schwensen undertook a study of a 1988 model 95kW turbine in (Grum-Schwensen 1996), but used questionable methodology to calculate the energy payback period for the wind turbine design under consideration. This combined with the age of the dataset used in the research, meant that its results were dated and of limited practical use. One of the most cited works with regards to energy payback times for wind turbines is that by Krohn (Krohn 1997). Using I/O analysis and information for onshore and offshore wind turbines, he concluded that they would pay back the energy invested in them in little under 3 months. Despite the widespread popularity of the work within wind energy circles, the work was carried out with regards to Danish conditions which are characterised by a large proportion of energy generation from renewables, and are therefore not necessarily representative of other locations. Schleisner (Schleisner 2000) concentrated on the assessment of energy and emissions from the production and manufacture of materials for an onshore and offshore wind farm in Denmark, using a LCA. The work produced similar energy payback periods to the aforementioned work by Krohn. It also analysed the associated externalities with the wind farms and placed an economic value on them, concluding that up to 93% of the associated emissions from wind power are due to the manufacture of the wind turbines themselves. He also stressed the advantages of the ability to recycle wind turbines at the end of their lifetimes.

In Canada, the Pembina Institute undertook what they termed a Life Cycle Value Assessment (LCVA), with the stated purpose of encouraging the uptake of wind power in the country. The study calculated the GHG emissions for the Alberta grid’s natural gas fired power stations and wind farms, with the aim of calculating the emissions that could be avoided by wind generated electricity. The group concluded that wind power was by far the most environmentally benign option of those considered but the total avoided emissions that could be realised depended on the type of fuel with which wind was compared, as well as on the conditions of the wind site location.

Approaching wind power, from a slightly different angle, Denholm et al (Denholm, Kulcinski, & Holloway 2005) considered the possibility of combining wind power with large scale energy storage in the form of compressed air energy storage (CAES) in the U.S., to provide baseload power. The work concluded that this would result in emissions that were only 20% of those associated with next lowest emitting baseload power plant (natural gas fired combined cycles), while also reducing other associated emissions (such as methane and CFC gases). Other work that looked at the combination of wind with backup systems include (Khan, Hawboldt, & Iqbal 2005), who investigated a wind-fuel cell combination and compared to it to diesel systems used for backup in remote communities, concluding that positive benefits could be achieved from the use of wind power. Yoshishige et al (Yoshishige Kemmoku 2002) also arrived at similar conclusions in their work looking at a wind/solar/diesel system.

One of the most extensive studies of wind power generation has been the work carried out by Lenzen and Munksgaard who summarised the energy and emissions results from a large number of wind turbine-related studies, in the last two decades (Lenzen & Munksgaard 2002). It, like previous studies, concluded that there was considerable scatter in results for both energy and emissions and that apart from differences in analysis methodology and scope, the scatter in energy intensities was probably caused by economies of scale and by differences in lifetime, load factor, technology and country of manufacture.

Of direct relevance to the current work is an assessment of photovoltaic and wind power that was carried out by Jungbluth et al, using the Ecoinvent database (Jungbluth et al. 2005). The work focused mainly on the evaluation of the relative importance that the different lifecycle stages played for each technology as well as the importance of external parameters such as location and energy mixes. It also stated that previously reviewed work differed in scope, but showed the dominant influence of the material production on the environmental performance of wind power plants. More recently many electricity utilities have been using a new method of appraisal, based on a quasi-LCA style methodology, to generate Environmental Product Declarations (EPD) for the electricity they generate. These reports focus mainly on GHG emissions and other environmental impacts such as resource use, while energetic parameters (such as gain and payback ratios) are not investigated. Vattenfall, a Swedish multinational utility, produced an EPD in 2003 (Vattenfall AB 2003), which calculated the GHG emissions of the electricity produced from their Swedish wind farms. Another report from the Italian utility ENEL provided an evaluation of the performance for a wind farm in southern Italy (Enel SpA 2004). Further work related to Italian wind farms, using an LCA approach was also conducted by Ardente et al , in an assessment that looked at energetic parameters (energy gain ratio, energy payback periods etc) as well as emissions (Ardente et al.). They also displayed the avoided emissions from the wind farms operation by taking the average Italian grid mix emissions factor as the unit of measurement and comparison.

From an academic point of view, Wagner and Pick provided an analysis of energy ratios and cumulative energy demand, in their work based on generic wind farms at locations with different wind speeds (Wagner & Pick 2004). They concluded that wind paid back its energy investment in 3-7 months. Tryfonidou and Wagner also researched the same parameters for a large scale wind turbine (5MW) arriving at similar energy payback times (Tryfonidou & Wagner 2004). An assessment of a 2 MW wind turbine using information provided by the manufacturer GAMESA, was carried out by Martinez (Martinez et al. 2009) for an onshore location in northern Spain, using LCA methodology. The assessment focused on the evaluation of manufacturing, operational and disposal stages of the lifecycle and calculated payback times of 0.58 months and energy gain ratios of approximately 34. The avoided emissions were estimated in similar fashion to the work of Ardente, using the Spanish electricity grid mix. Other studies relevant to this work, have been those conducted by individual researchers such as Ancona who looked into establishing empirical rules to scale material requirements for wind turbines (Ancona & McVeigh 2001), based on previous studies. Similarly, Hopf also looked at the energy requirements of large scale wind turbines (Hopf et al. 2001) as did (Geuder 2004).

Organisations directly related to the wind turbine industry have also published relevant works, such as the British Wind Energy Association (BWEA) in (BWE 2007;BWEA 2006;BWEA, BVG Associates, & Westwood 2006). Special note also needs to be made of the studies published by wind turbine manufacturers and utilities, mainly in Denmark (Elsam Engineering 2002;Elsam Engineering A/S 2004;Vestas Wind Systems A/S 2005). These studies provided a substantial amount of information on the material and energy inputs for modern wind turbines.

Special mention has to be made about reports related specifically to the assessment of offshore wind farms. Although work in the field is fairly limited, one of the first integrated assessments of offshore wind was undertaken by Germanischer Lloyd in 1995 (Germanischer Lloyd & Garrad Hassan 1995), largely for theoretical designs and conditions. Similarly, the Danish Energy Agency undertook similar work for the IEA CADDETT programme (IEA CADDET & Danish Energy Agency 2000). The environmental organisation Greenpeace also undertook a study into the offshore wind potential in the North Sea in the U.K. in (Söker et al. 2000). Another major study was coordinated by the TU Delft under the auspices of the European Commission and involving many components of the wind industry. The report, titled “Concerted Action on Offshore Wind Energy in Europe” (CA-OWEE 2001), covered all major aspects of the, then still developing, offshore projects. The consultancy Garrad Hassan also published work into the operational and economics of offshore wind in their report (Garrad Hassan 2003) with Greenpeace commissioning a further report from them in 2004 (Greenpeace & Garrad Hassan 2004) to investigate the potential of using offshore wind to meet 30% of E.U electricity requirements. More recently, the Carbon Trust in the U.K. undertook a study into the potential for offshore wind in the country (Carbon Trust 2008). In the U.S. the National Renewable Energy Laboratory, undertook a similar study on a smaller scale for a conference (Musial, Butterfield, & Ram 2006).

A useful review of technologies and the current status of the technology was presented by Breton in (Breton & Moe 2009) while lifecycle assessments of offshore wind farms have been undertaken by Properzi and Herk-Hanson in (Herk-Hanson, & Properzi 2002). Assessments of currently operating offshore wind farms have been carried out by a variety of researchers and organisations as can be seen from the reports of (AMEC Energy Ltd & DTI 2004),(ENERGI E2 A/S 2005),(Pedersen 2006); while environmental impact reports include studies by (Elsam Engineering 2002),(Elsam Engineering & ENERGI E2 A/S 2005), and reviews such as (Herk-Hanson et al. 2006),(Carter 2007) and (Larsen et al. 2005). The International Energy Agency also published a review of current knowledge in (IEA, Stenzel, & Pflueger 2005).

Experience on the “Back End” of the offshore wind cycle is fairly limited as most installations are only currently coming to the end of their operational lives. Studies on the decommissioning of offshore wind farms has been undertaken mostly in Denmark as can be seen by Pearson (Pearson 2001) and Feld et al (Feld.T., Hjortbak, & Sørensen.P.H 2004). Similarly reports were prepared for the decommissioning of the Greater Gabbard wind farm in the U.K. (Greater Gabbard Offshore Winds Limited 2007).

2.4.1.3 Studies related to nuclear power

One of the first ever studies on nuclear power, as stated earlier, was conducted by Chapman, as part of his analysis on the emerging nuclear program in the UK in the 1970s (Chapman 1974b). His original work critisised nuclear power as a net energy consumer, especially under scenarios of large-scale deployment. These claims provoked a string of publication by other researchers backing or refuting Chapman's claims (Chapman 1975a;Chapman & Mortimer 1974;Chapman 1975b;Hill 1975;Hollomon 1975;Sweet 1978;Wright & Syrett John 1975). Work on the same subject was also undertaken by the IAEA in (Held et al. 1977), concluding that nuclear power did not run the risk of consuming more energy than it produced, while it was also a low carbon dioxide emitter. At around the same time, work was also being carried out in mainland Europe and the US on the energy and material requirements of nuclear power stations and their fuel cycles, as can be seen in the work by (ERDA-76-1 1976;Inhaber 1978) among others. In the early Eighties, Tsoulfanidis provided an analytical net energy analysis of nuclear power (looking at both fission and fusion technologies) using a hybrid I/O and Process analysis approach (Tsoulfanidis 1981). He also concluded that nuclear was a low carbon emitter.

In the 1990s, various institutions and individual researchers published reports on nuclear power such as (CEC & CEPN 1995;Collier 1993;Curtiss, Dreicer, & Rabl 1996;Hammond 1996;IAEA 1996;ORNL, Resources for the Future, & DoE 1995;Stumpf 1995), evaluating its environmental performance up to that point in time, making predictions about future developments and questioning its necessity, given the economic and energetic performance thus far displayed. An analytical study of work related to energetic indicators based on Net Energy Analysis, was presented by the IAEA in (IAEA 1994). Although the work did include results for other technologies it focused more specifically on nuclear power. However the main impetus behind the work was to define whether or not nuclear power was a net energy producer and therefore did not focus on other environmental impacts.

With the resurgence of interest in nuclear power generation, as a result of increased concerns about the effects of global warming due to human activities, the emphasis shifted to the analysis of the environmental performance of nuclear power generation.
One of the most widely quoted works to support the view that nuclear power emits significant quantities of carbon dioxide throughout its lifecycle, was presented in the Hinkley Point PWR consultation by Friends of the Earth and Mortimer (Mortimer & Friends of the Earth 1989). Mortimer's argument was centred on the depletion of high grade ores which subsequently lead to higher CO_2 emissions because uranium extraction from lower ore grades would need more fossil energy.

A report by the German Öko-Institut supported the view that nuclear power had higher emissions than renewable or cogeneration gas fired plants (Oeko Institut & Frische 1997). The work was further revised in 2006 (Oeko Institut & Frische 2006), with updated datasets and better cost estimates, but still arrived broadly at the same conclusions. Rashad et al (Rashad & Hammad 2000) also assessed a variety of electricity generation fuel cycles and concluded that, with respect to GHG emissions, nuclear produced the lowest emissions (9-30 gCO_2eq/ kWh), followed by wind (11-75 gCO_2eq/ kWh), hydropower (16-410 gCO_2eq/ kWh) and finally photovoltaic power plants (80-279 gCO_2eq/ kWh). Research conducted by Dones et al on an assessment of the nuclear and natural gas fuel cycles (Dones, Heck, Faist Emmenegger, & Jungbluth 2005) concluded that for centrifuge enrichment-based nuclear fuel cycles, nuclear emissions could be as low as 5 gCO_2eq./ kWh. In research on electricity and heating systems in (Dones & Heck 2006), he went on to conclude that nuclear power demonstrated generally good environmental performance, unless high-level radioactive wastes were given subjectively high negative value. Other work such as Tokimatsu et al (Tokimatsu et al. 2006) for Japanese conditions concluded that nuclear power was indeed one of the lowest emitting technologies and its uptake should therefore be encouraged in the context of GHG emission reduction policies. More recently Fthenakis et al (Fthenakis & Kim 2007) undertook a comparison of nuclear and solar power for U.S. conditions, concluding the both technologies had similar emissions.

From a policy standpoint, several influential reports have been published about the future role of nuclear power and its implications. One of the first reports to endorse nuclear power in the last decade, was published by the U.K.'s Royal Society (Royal Society & Royal Academy of Engineering 1999). This report highlighted the need to keep the nuclear option open, at a time when the government seemed poised to phase out the country's nuclear capacity. A further influential interdisciplinary study was undertaken by the M.I.T. (Massachusetts Institute of Technology 2003) where the all major aspects of the nuclear fuel cycles were considered, with a special emphasis on the economic prospects of the energy supply system. The study presented overall a cautious but favourable assessment. More recently, the Sustainable Development Commission, the UK Government's independent watchdog, also prepared a multi volume assessment of nuclear power, The SDC's review on nuclear power was prompted by the U.K.'s 2006 Energy Review and took a negative view, arguing that nuclear power was too expensive, inflexible and also raised serious questions about nuclear waste treatment and international nuclear terrorism.

Two studies that have generated considerable interest and discussion in the field of nuclear power generation require special mention. The first is the work by researchers Storm van Leeuwen and Smith which was centred on the question of the sustainability of the nuclear fuel cycle, given ever increasing growth rates and the depletion of high grade ores (Jan Willem Storm van Leeuwen & Philip Smith 2005). The arguments put forward echoed in many ways the research of the previously mentioned work of Mortimer (Mortimer & Friends of the Earth 1989) and have met with criticism from a range of sources, mainly due to the age of the dataset used and for some of the assumptions utilised which, it was claimed, did not reflect real life practises. The second piece of work that deserves special attention is that of the World Nuclear Association, which was published in response to the first. The World Nuclear Association published work on their website to refute the previous researchers' claims (WNA 2005a), which in turn was answered by Storm van Leeuwen and Smith in subsequent publications (Storm van Leeuwen 2007). A similar discussion was also conducted between the aforementioned Storm van Leeuwen and researchers at the University of Melbourne, with both research teams subsequently generating a list of publications, refuting each others arguments (see (Sevior 2005), (Storm van Leeuwen 2005) and subsequent responses).

One of the most recent and extensive pieces of research can be found in the publication of the Integrated Sustainability Analysis (ISA) group from the University of Sydney (ISA 2006). The work provided an extensive summary of studies carried out on the nuclear fuel cycle and undertook modelling for a hypothetical nuclear scenario in Australia. In that work and in resulting journal papers (ISA 2006), Lenzen et al stated that, while greenhouse gases from nuclear power were lower than those of fossil technologies they were higher than reported figures for wind turbines and hydroelectricity and of the same order as those from solar photovoltaic or solar thermal power. The work by ISA was based however, mainly on the use of I/O data, which as previously stated results in higher estimations of emissions and energy requirements than other studies. The work also contained a section once again demonstrating that the claims made by van Leeuwen and Smith could not be supported. On the same note, a further critique of the Storm van Leeuwen study was issued by Dones, who used the most up-to-date data available to demonstrate that the nuclear fuel cycle’s emissions were substantially lower than those quoted by the aforementioned researchers (Dones 2007).

One of the most recent and most extensive studies to date on the emissions of the nuclear fuel cycle was published by Sovacool in (Sovacool 2008). The study summarised 103 previous lifecycles studies and concluded that there was a broad range of results for GHG emissions (1.4 – 288gr /kWh) from nuclear power. One of the main findings of the study was that it was extremely difficult to compare studies based on different assumptions, while the author also stated that there was a clear need for more up-to-date and transparent studies on the lifecycle. The work was limited however to compiling previous works on the subject and did not offer any new information.

Of special interest to this current research are also the reports and studies published by nuclear utilities in the UK and abroad. Among the first to conduct a study into the impacts of their facilities was the Swedish utility Vattenfall, which published environmental impact reports in the form of Environmental Product Declarations, in similar fashion to the Danish wind turbine manufacturers (Dethlefsen et al. 2006;Vattenfall AB 2004a;Vattenfall AB 2004b;Vattenfall AB Generation Nordic Countries. 2004). In the UK, similar work was also carried out by the nuclear utility British Energy for one of their nuclear power plants (Torness) (AEA Technology & British Energy 2005;AEA Technology & British Energy 2006). The conclusions from these reports were also an indirect rebuff of the van Leeuwen and Smith assertions that lower grade ores would dramatically increase the GHG emissions emitted by the nuclear fuel cycle.

2.4.2 Energy Density

The literature regarding the Energy Density for whole energy supply systems i.e. the land required for an energy supply system to provide a unit of energy, is relatively limited.

Most assessments of this parameter have been undertaken as part of larger studies into a wide range of parameters. Friedrich and Manheineke looked into the Energy Density requirements of several technologies under German conditions, including wind and nuclear power, in (Friedrich & Marheineke 1994). Similarly, Van de Vate, looked at the parameter of Energy Density for wind and solar power (Van De Vate 1996b) from the perspective of describing the sequestered land as a "negative carbon sink". Gagnon et al also assessed land use as part of an LCA of different technologies (Gagnon, Belanger, & Uchiyama 2002) concluding that nuclear had a significantly better Energy Density than wind, while the latter actually had the third worst Energy Density performance of the assessed technologies.

Pimentel et al in (Pimentel, et al 1994) also made an assessment of various alternative technologies for the U.S., stressing that an immediate priority is to speed up the transition to renewable energy technologies. Among the parameters investigated were the land requirements for each technology reviewed, without however placing an emphasis on the calculation of energy densities per se. A qualitative approach to land requirements was provided by Ausubel in (Ausubel 2007), who proceeded to argue on the basis of this indicator that nuclear power should be considered more "green" than renewables. Energy Density and an associated indicator, Power Density, were also used by Smil (Smil 2006), to argue the difficulties of the transition to renewable sources, by highlighting the diffuse nature of wind power.

Work that looked specifically into quantifying and characterising the land use of energy supply systems can be seen in the works of Fthenakis. Most recently Fthenakis and Kim (Fthenakis & Kim 2009) reviewed and updated land requirement values for a range of technologies, under U.S. conditions, arguing that PV have the lowest requirements while biomass the largest. Finally, an overview of various parameters relating to the sustainability of renewable energy was published by Evans et al in (Evans, Strezov, & Evans 2009), based on a literature review. The work however was not extensive enough to allow the drawing of any conclusions.

2.4.3 Material use and natural resource depletion

Previous work on material requirements and their effect on resource depletion for different technologies is generally limited.

The quantities of materials required for wind and solar power are described by van de Vate in (Van De Vate 1996b). The report however, did not attempt to normalise the values and hence did not draw any direct comparison between the technologies. Material use in the form of common construction materials were also presented by Voss in (Voss 2001), where it was argued that nuclear had some of the lowest material requirements per unit of electricity produced from all energy supply technologies investigated. A more aggregated presentation of resource requirements per kWh was given by Lund in (Lund 2007), where the conclusion presented was that the level of resources required for renewables were the same order of magnitude as those for nuclear power.

With the exception of the aforementioned works, few other studies have been published that are of direct relevance to the current work. This in itself demonstrates that there is scope for further research in this area.

2.4.4 Water

Water use, especially by energy supply systems, is one of the most underreported resources in the evaluation of sustainability. The link between water and energy has been highlighted by the U.S. Department of Energy in (DoE 2006). Although the approach they adopted is not the same as the one used in this research, the fact sheet they produced did highlight the benefits that wind power could provide, such as reducing the water consumption of the energy sector, providing water through desalination and the benefits of combining wind power with hydropower.

More inline with the approach of this current research, an assessment of both the energy requirements for water as well as the water requirements for energy production was undertaken by Gleick in (Gleick 1994). That report stated that the water usage by renewables was significantly lower than those of conventional generation, while wind power was estimated to use negligible quantities. Nuclear on the other hand, was amongst the highest users of waters in the conventional generation category.

The effects specifically of biomass production on water resources was investigated by Berndes (Berndes 2002), who highlighted that this form of energy source could in some countries exacerbate water shortages but also that in general, assessments of bioenergy potentials need to consider restrictions from competing demand for water resources. Focusing on the U.S., Inhaber (Inhaber 2004) argued that renewables could have water use per unit energy comparable to conventional systems, when the entire cycle is considered (including possible backup). The opposite viewpoint was supported by von Uexküll in the article (von Uexküll 2004), quoting values from Gleick, arguing that "the global water crisis cannot be solved without a complete shift of global energy production to RE [Renewable Energy]".

The importance of water use and the requirements of the energy supply industry have become more prominent recently. Feely et al conducted a study, again from a U.S. perspective, into water usage of the thermoelectric energy generation sector (i.e. coal, oil, natural gas fired and nuclear) (Feeley III et al. 2008), in order to highlight the critical role that water played in these systems and the need for its conservation.

Water use was also covered by Evans et al in (Evans, Strezov, & Evans 2009), focusing specifically on renewable energy technologies. However, the values quoted in that study were taken mainly from Inhaber (Inhaber 2004) and therefore arrive at the same conclusions, namely that wind power was demonstrated to have the lowest water requirements per unit energy produced.

2.4.5 Avoided emissions

Previous work on the emissions avoided by implementing a low or zero carbon technology is limited in scope and quantity, mainly due to the fact that the significance of this parameter has only recently been recognised. The main impetus for the investigation of this parameter in this current work can be attributed to research by the Renewable Energy Foundation (REF) in the U.K. which questioned the current use of *avoided emissions factors* to estimate the contributions of wind power, which were either based on average grid emissions or coal-fired power stations which are generally considered to be the most GHG emission intensive sources on the Grid (White & Renewable Energy Foundation 2004). The main argument of the report was that the variability of wind power generation necessitated the part-loading of traditional (fossil fuel) power plants as stand-by generation, leading to a decrease in their operational efficiencies and an increase in their associated emissions. Thus the report in effect questioned whether wind energy could be considered “green” when its impact on other power plants on the grid was also included. The claims of that research were refuted by the British Wind Energy Association in (BWEA 2005), which justified the use of those emissions factors by quoting earlier work by the U.K.’s, now-defunct, Central Electricity Generation Board. There are several studies that investigate an appropriate methodology for assessing the avoided emissions such as (OECD & IEA 2000), (NEI 2003), (Kartha, Lazarus, & Bosi 2004), (Biewald 2005) focusing mainly on providing guidelines for Clean Development Mechanism (CDM) projects. Other researchers have provided guidelines specifically for assessing the contributions of wind projects (Gil & Joos 2007). One of the most concerted efforts was undertaken by the World Resources Institute, which published several reports on the subject (see for example (World Resources Institute & World Business Council for Sustainable Development (WBCSD) 2005) and (World Resources Institute & Broekhoff 2007)). From the perspective of estimating avoided emissions from demand side management, work by Schiller (Schiller 2007) illustrated the requirements for meeting the recommendations of the U.S. government’s National Action Plan for Energy Efficiency. Most recently the National Renewable Energy Laboratory published a summary of the impact of wind energy development on various air pollutants for a general audience (Jacobson, High, & NREL 2008). It is interesting to note that certain utilities, mainly in the U.S. and Canada, have attempted to provide methodology and the avoided emissions calculations for their generation mix (see (Bullfrog Power 2008))

In the U.S., High and Hathaway evaluated the avoided emissions of selected air pollutants from three potential wind energy projects in Virginia (High & Hathaway 2006) concluding that the projects did indeed avoid significant amounts of emissions. For the U.K., Bettle et al (Bettle, Pout, & Hitchin 2006), building on earlier work (Hitchin & Pout 2002), considered the actual avoided emissions by investigating the relationship between electricity demand reduction and the consequent change in carbon emissions, using more detailed modelling than previously. The researchers concluded that the carbon savings are consistently greater than those calculated from the annual system average emission factors. However, this work focused on the effects of end use variations rather than supply side changes.

2.5 Conclusions from Literature Review

From the literature review conducted in this work, certain conclusions can be drawn. It can generally be said that there is only a limited number of integrated assessments that contain all the indicators being considered in this current work. Even in the cases where all, or most, of the indicators and impact categories have been considered by previous works, very few studies maintain consistent boundary conditions. This issue is further complicated by the use of different energy accounting procedures and assumptions which are not always expounded clearly. These points ultimately mean that the differences in assumptions make the evaluation of parameters in the same study problematic, and even more so when comparing the results of different studies.

Another conclusion from the review of available literature and information is that there are still only a limited number of studies dealing with offshore wind farms. This, in many ways, is to be expected given the lack of maturity of the technology and the dearth of publically available data. However, there is a clear need for further work in this field. A point that applies to all the above conclusions is the fact that only a small fraction of research in the above literature has been conducted for the conditions that exist in the U.K. While there are numerous studies dealing with generic sets or applied to other countries (i.e. United States, Germany etc), the conclusions cannot automatically be applied to a U.K. context.

A subject that has not received much attention until recently has been that of the actual quantities of emissions avoided by the use of near-zero carbon energy supply systems. The issue of avoided emissions has only recently become important with the growing understanding of the interconnectedness of systems. As such, there is a limited body of work addressing this aspect, and even less that actually attempts an in-depth analysis of the numbers utilised. There is clearly a need for more work in this area. It is also important to note that a large body of literature is based on datasets that do not necessarily reflect current conditions and practises, and even less future scenarios. This means that in order to contribute a relevant assessment of different energy supply systems, it is imperative that the most current data is utilised.

Despite the number of publications in the field, the debate surrounding both renewables and nuclear power has yet to be resolved, therefore necessitating further studies, using the most up-to-date information available. It is important to point out that rarely in studies on the topic are all the assumptions clearly outlined, while there is a clear need for unbiased and non-weighted results to aid reproduction of work and balanced opinion forming.

3. Research Methodology

The purpose of this chapter is to outline the methodological approach adopted in this piece of research and to clarify the basic concepts and definitions used throughout the work. The chapter describes the data sources used and presents the theoretical background of each indicator that is subsequently used in this work. It also provides analytical explanations of the conventions adopted to allow the comparison of the different power plants assessed in this work.

3.1 Information sources and databases

The modelling work carried out in this project has consisted of desktop-based research, using information from publicly available reports, both academic and industry related, as well as proprietary databases compiled by research institutes and international organisations in relevant fields of research. The information taken from reports is discussed in each section where it is used, with the main sources of reference already having been described in Chapter 2. The information compiled for this research project consists mainly of data taken from industrial environmental statements, annual reviews, corporate and social responsibility reports and relevant publications from environmental organisations and non governmental organisations. Academic literature was thoroughly reviewed for further information and data from peer-reviewed reports and journal articles was incorporated into this work, where applicable. The aforementioned literature provided data on the current status of the technologies under investigation, operational data from recent and currently operating facilities as well as insights into industry standard practises.

For other aspects of the modelling work, however, it was necessary to use information from databases compiled by research institutions. This information consisted mainly of data on “background” systems (i.e. data on the energy and material requirements for second tier inputs and above to the systems). It was also used to supplement the information provided in specialist literature, where the lack of information in certain areas would have meant significant gaps in the knowledge and subsequent modelling of the subject matter.

The main database used in this work is the Ecoinvent Database v2.0, provided by the Swiss Centre for Life Cycle Studies (Frischknecht 2005). The database covers over 4,000 datasets for products, services and processes commonly used in Life Cycle Assessment studies. It contains information on a variety of systems such as non-renewable and renewable energy systems, building materials, metals, packaging materials, chemicals, agriculture, transport services and waste treatment and disposal (Frischknecht et al. 2004). The goal of the Ecoinvent project has been to generate a set of generic, uniform and consistent life cycle inventory (LCI) data of high quality for the aforementioned areas. The selection of entries analysed in the database are based mainly on the market situation in Switzerland for the year 2000. Because Switzerland's economy is closely linked to the surrounding countries, it is claimed that a lot of processes are also valid for the situation in other countries in Europe, as well as conditions in some non-European countries. This is especially the case in such processes as mineral extraction and the extraction and processing of energy sources (gas, oil etc). It should be noted that in this current research work, where some entry in the Ecoinvent database was felt to be unrepresentative of U.K. conditions, it was modified accordingly. As previously stated, the reference year 2000 was applied wherever possible and the geographical system boundary was principally comprised of the entire world. However, for regions where data availability was rather poor, processes could not be modelled with actual, country-specific data. In such cases assumptions were needed and based on best available information. The processes included in the Ecoinvent database represent, in most cases, the average level of technology currently in operation. Emissions from previous temporal stages such as the past (i.e. infrastructure construction), the present (e.g. heating) and the future (e.g. disposal options) are all included in the inventory analysis without temporal boundaries (Frischknecht 2005). This in effect means that it is not possible to differentiate on a temporal basis when each action or process occurs, and only a cumulative representation of all the actions/processes is possible. This shortcoming in the methodology is highlighted in later chapters, but is seen as an unavoidable side effect of time constraints and using highly detailed data. Uncertainty of flow data is quantified at the level of each individual input and output of each described processes. If the uncertainty cannot be quantified (because it is not stated in the sources used or because it is not actually known by the source providing the data) a standardised estimation procedure is used (Frischknecht & Rebitzer 2005).

3.2 Boundary conditions

To evaluate the performance of each system on a lifecycle basis, it is necessary to define the boundary conditions for each of the different stages that contribute to the final product. Therefore, in order to create the model of each power station, the process stages of each technology need to be defined; this way the inputs and outputs that are included within the scope of each power plant lifecycle can be highlighted and the impacts from those processes can be attributed to the final product of each system, in this case the electricity they produce.

3.2.1 Wind farm

The boundary conditions of the wind farm include the stages of material production, transportation of components and site construction, the operational requirements of the wind farm and the final dismantling and disposal/recycling of components. The stages (with their associated boundaries) taken into account in the life-cycle analysis are described in the diagram below:

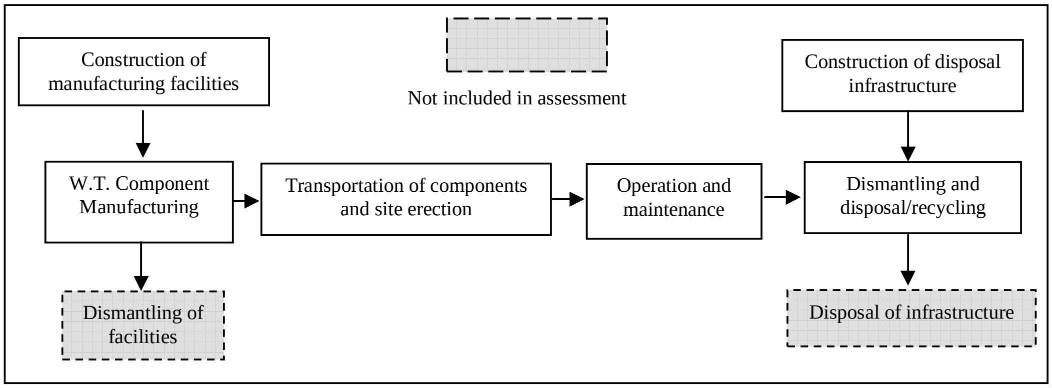


Figure 3.1 Boundary conditions for the wind farm lifecycle models

3.2.2 Nuclear power station

The following processes are included in the lifecycle boundaries of the assessment of the nuclear power station:

- Extraction, refining and conversion of uranium ore
- Fabrication of the nuclear fuel (including conversion, enrichment and fuel rod manufacturing)
- Operation of the nuclear power plant
- Relevant transport of materials and equipment
- Construction, operation and dismantling of the nuclear power station
- Construction and operation of the facilities pertaining to outputs/wastes related to the operation of the nuclear power plant.
- Conditioning of the nuclear wastes, as well as the resulting wastes from the decommissioning of the power plant

The processes are illustrated diagrammatically below:

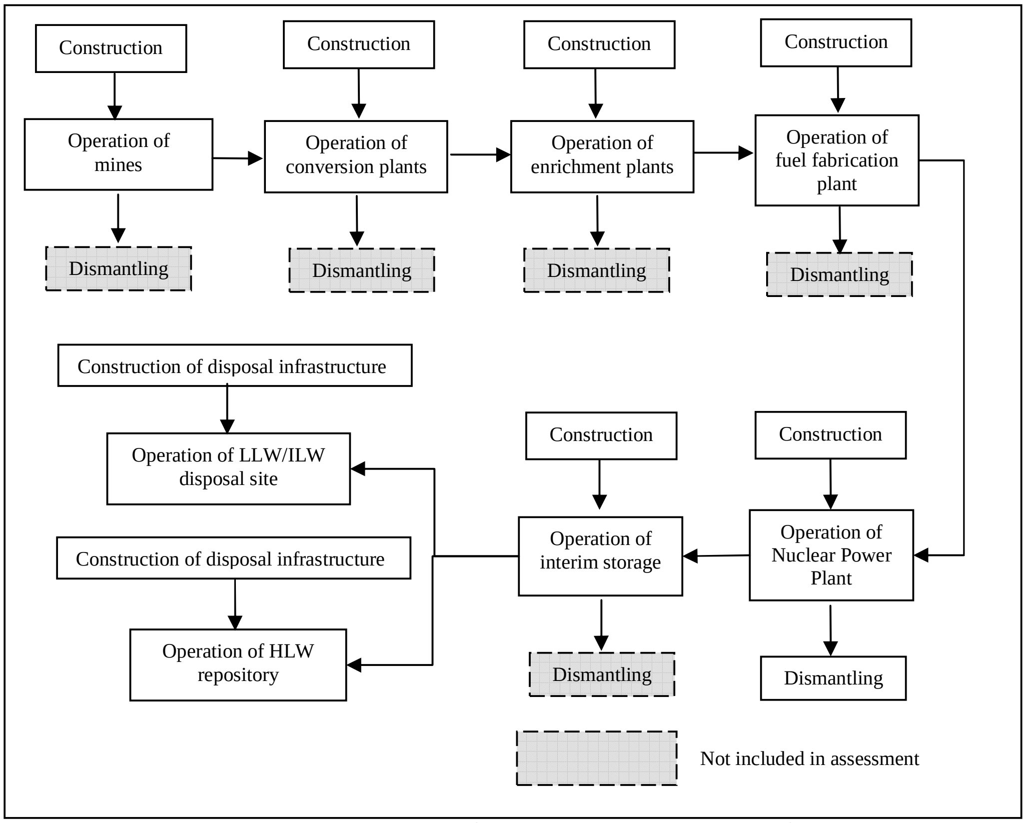


Figure 3.2 Boundary conditions for the nuclear power plant lifecycle model

3.3 Recycling methodology

A major stage in the lifecycle of any product is the end-of-life treatment it receives. This means that the processes that are applied to a product once it has completed its useful operation and its disposal. One of the major options for treatment which is especially promoted in the light of Sustainable Development is that of recycling. As such, an important note needs to be made about the recycling assumptions used in this research. For the nuclear power cycle, it has been assumed that no recycling of building materials or fuels is undertaken. This means that at the end-of-life of the power station and its supporting facilities, all materials are disposed of either in landfills or through incineration (for building and supporting materials) while spent nuclear fuel is stored indefinitely. For the wind power cycle however, in accordance with previously published work, it has been assumed that a large percentage of a wind turbine is recycled or re-used (approximately 90% for most major materials) once they reach their end-of-life. An analytical breakdown of the disposal/re-use scenarios is presented in Section 6.2.9.1. This assumption however presents certain challenges with respect to the recycling methodology espoused. Although various theories exist for how to account for the benefits and drawbacks of recycling, the two most prominent approaches are the 'substitution' approach and the "recycled content" approach.

The 'substitution' method utilises an approach where the material inputs to the system are from primary sources, but the quantities of materials required, are reduced by the *quantity of the recycled materials assumed to be recovered from the system's own life cycle*. This approach however, means that the credit for recycling is applied internally in the system and therefore can only be applied when the inputs are originally from primary sources (i.e. do not contain recycled materials in the first place) as this would lead to double-counting the positive impacts in the recycling system. A diagram (taken from (Hammond & Jones 2008)) illustrating an example of this can be seen below:

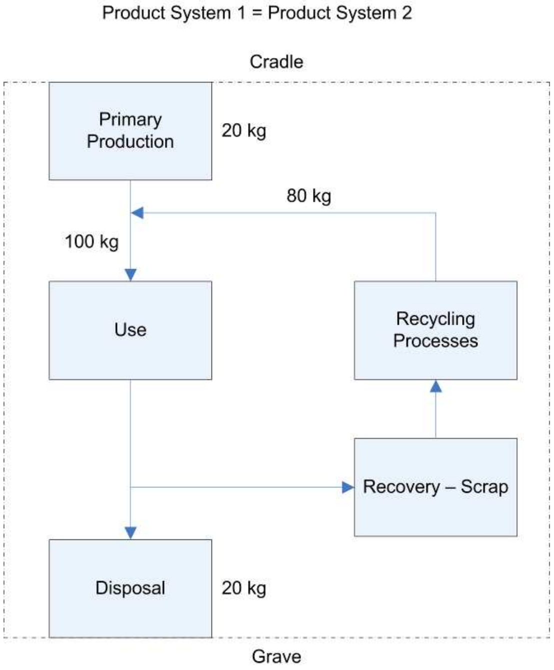


Figure 3.3 Substitution method

The "recycled content" method is based on an approach whereby the benefits of the material outputs (i.e. the materials that are to be recycled) from one system are attributed to *the future user* of these materials. Thus, it is the subsequent user of the recycled materials that is credited for the avoided impacts and *not* the system or user who produced the recycled materials in the first place. A diagrammatic representation (taken from (Hammond & Jones 2008)) can be seen below:

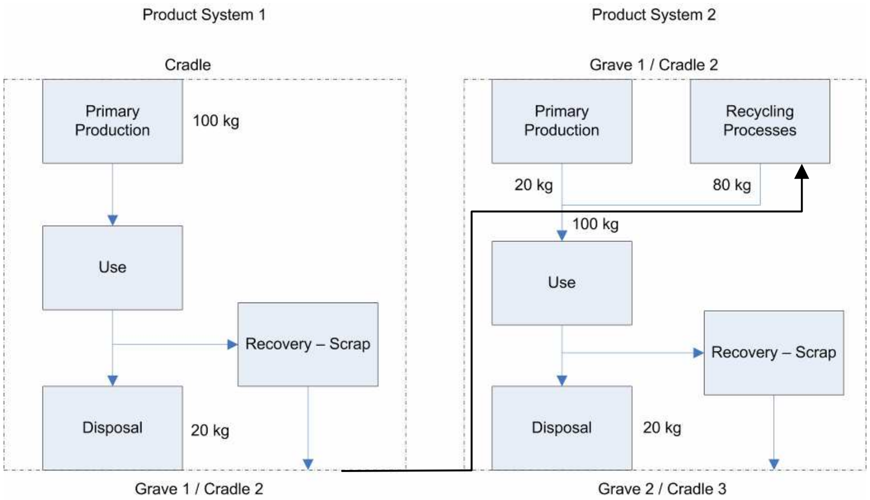


Figure 3.4 Recycled content method

The material inputs into this modelled system already include recycled materials (in effect reflecting reality where materials and especially metals are a mix of primary and secondary sources). Hence to include the benefits of recycling the materials in the same system would lead to double counting. This "recycled content" approach is suggested by the ISO guidelines on LCA, and has been used most recently by the U.K.'s Carbon Trust in their report on the assessment of lifecycle GHGs for goods and services. It is also the method adopted in this current work, as it thus allows for a fair basis of comparison between the nuclear power cycle and the wind power lifecycle. This is due to the fact that it has been assumed that no recycling of materials takes place for the nuclear lifecycle; however, it is possible that certain materials are recycled from the dismantling of power plants. Thus, using the substitution method (which credits the benefits of recycling to the same system) would mean that this difference *in assumptions* between the nuclear and wind modelling would be exacerbated. With the crediting of recycling benefits to the next system, on the other hand, it is possible to use an average mix of input materials, which is more representative of real life conditions, as well as making sure uncertainties about the end-of-life treatment do not unduly affect the boundary conditions of the models.

3.4 Functional unit

According to the ISO 14040 standards (ISO 1997), the *functional unit* can be defined as :

"The quantified performance of a product system for use as a reference unit in a life cycle assessment study"

An alternative definition is provided by Boustead in (Boustead & Boyd 1996):

"… the parameter that measures the environmental performance of the system and serves as a reference to which all input and output data is normalised"

As the two power plants operate under completely different fuel cycles, it is necessary that the functional unit is based on the similarity of their product. Since the purpose of both power plants is to provide electrical output, the results of the study are based on the functional unit of:

“1 kWh of electricity generated at the power plants in the reference time-frame”

Therefore, all impacts are estimated for this functional unit, making the results comparable with those of other evaluations of electricity generating technologies. In the case of this work, the definition is extended by the addition of the clause that the electricity is transmitted through the distribution system (i.e. the electricity grid) to end-use, thereby including the associated efficiency losses through thermal and magnetic effects in the wires. It does not include however the “end-use” of the electricity, as it was decided the inclusion of this phase of the lifecycle does not add anything to the comparison. It should be noted that the end-use is not normally included in the system boundaries, when the objective of the assessment is to determine the net energy yield of energy supply systems. In some cases, end-use may be an integral part of the system i.e. solar heating, in which case, its omission would make any comparison between even similar systems meaningless.

3.5 Comparison criteria

A description of the various indicators used to compare the different energy supply systems is given below. In all cases, the underlying theory is presented, together with a brief outline of the historical development and significance of each indicator.

3.5.1 Energetic indicators

This section contains a methodological description of the indicators devised to measure the energetic performance of the energy supply systems being investigated. It also includes a brief description of the nature of energy and of the background for the indicators’ development.

3.5.1.1 A description of Energy

It is possible to consider the world that surrounds us as a vast store of energy, available in various forms such as fossil fuels (e.g. oil, coal, gas etc), temperature gradients (whether oceanic or geothermal related), radioactive elements (uranium, thorium etc) and pressure gradients. In addition to these, there is a daily input of energy in the form of solar radiation. Some of this energy is available through the direct combustion of fuels, others (prime example: uranium) require processing before the energy can be made available for exploitation. Some others still (such as renewables), require specific processes and technologies to become useable as useful energy.

The study of the use of energy in the production and provisions of goods and services is termed Energy Analysis (EA). Generally, Energy Analysis is “defined as the determination of the energy sequestered in the process of making goods or services within a framework of an agreed set of conventions” (International Federation of Institutes for Advanced Study & IFIAS 1974). Energy Analysis can provide a more detailed understanding of the interdependences between various sectors of a system (and specifically a national economy) and a system and its natural environment. It can help identify the constraints and boundaries of a given system, by comparing the actual energy requirements of a process to the theoretical ones. This can then be used to access the development potential of processes. Adherents also state that EA can be used to complement conventional economic theory; it may highlight benefits that cannot easily be translated into economic terms as well as impacts whose future economic importance cannot be doubted but are difficult to evaluate in a contemporary economic context (Perry A.M, Devine W.D, & Reister 1977).

In thermodynamic terms, EA can be defined as the study of free energy changes. Free energy is the thermodynamic potential indicating the amount of energy released or absorbed in a reaction, assuming all processes are irreversible. However, as free energy changes are hard to quantify, another term called Enthalpy is usually used instead. Enthalpy (H) is a thermodynamic property representing the heat content of a substance and is equal to the internal energy (U) of the substance plus the product of pressure (P) and volume (V):

$$H = U + P \times V \qquad (3.1)$$

Enthalpy is the usual description of heat in thermodynamics, but the analysis of the production of a good or service in terms of heat can lead to significant errors under certain conditions. An example is that there is certainly more heat in the Atlantic Ocean than there is in the whole of the oil reserves of the Middle East (International Federation of Institutes for Advanced Study & IFIAS 1974). What makes oil more attractive however, is precisely the previously mentioned property of free energy. The First Law of Thermodynamics states that energy is always conserved but merely degrades in quality. The driving force for transformations is not the heat itself but the thermodynamic potential “free energy” which diminishes and is irrecoverable. This energy is known as the Gibbs Free Energy (G) and is defined as enthalpy minus the product of temperature and entropy:

$$G = H - T \times S \qquad (3.2)$$

Although early conventions (such as (International Federation of Institutes for Advanced Study & IFIAS 1974)) stated that the Gibbs Free Energy rather than enthalpy itself better addressed the objectives of energy analysis, it was demonstrated for most intensive fuels such as coal and oil, the error in taking H rather than G which was normally less than 10%. This was deemed acceptable, as it was recognized that in many cases it was actually impossible to calculate the free energy changes of actual processes (International Federation of Institutes for Advanced Study & IFIAS 1974).

3.5.1.2 Conventions used in energetic analyses

An important feature in Energy Analysis is the meaning of energy. As previously stated, thermodynamically, Energy Analysis is concerned with the study of free energy changes within a process. As a result of practical limitations, Energy Analysis is concentrated mainly on the heat released during the combustion of fossil fuels, although necessity requires that the heat generated by nuclear fission reactors and the energy flows available from renewable resources are also accounted for. In most situations the heat released during combustion is calculated by determining the calorific value of the fuel in question. For fuels, the higher Heating Value (also known as the Gross Calorific value) is more commonly used, and is defined as the energy that would be released if the fuel were to be combusted at standard temperature and pressure and includes the heat of condensation of the produced water. Another measure is the lower Heating Value (also known as the Net Calorific Value) and is the same as previous definition, excluding however the heat condensation of the water. Although a variety of methods have been developed, most analyses evaluate the total primary energy required for a given process.

Energy sources can be divided into primary and secondary sources. Primary energy sources are either extracted or captured directly from natural resources (oil, coal, gas etc), or are produced from primary commodities. All energy commodities which are not primary but are produced from primary commodities are termed secondary commodities (e.g. petroleum products or electricity). However both electricity and heat can be considered primary or secondary forms. Primary heat is captured straight from natural sources such as geothermal or solar thermal devices, while secondary heat is the heat available from the utilisation of primary sources (i.e. combustion of fossil fuels). Primary electricity is obtained from the conversion of natural sources such as hydro, wind, solar, tide and wave power. Secondary electricity on the other hand, is produced from the heat of nuclear fission of nuclear fuels, from the geothermal heat and solar thermal heat, and by burning primary combustible fuels (IEA, OECD, & Eurostat 2004). Primary energy sources which can be utilised by energy conversion technologies can themselves be classified in two major groups: nonrenewable and renewable sources.

Non-renewable energy sources are based on finite resources which were set down over a long period of time and cannot be regenerated on time scales comparable to their consumption i.e. are depleted through their utilization. Simply put, they form a natural capital that is being consumed faster than it can be replenished by Nature. Non-renewable sources of energy encompass fossil fuels (e.g. coal, oil, natural gas), which are natural sources of energy that were formed from the processes that biomass underwent in the geological past, and nuclear fuels which were created during the formation of the Earth and are self-depleting since their availability to produce energy reduces as they decay naturally.

Renewable sources of energy are sources that can be replenished by natural processes on timescales similar to those of their consumption and in effect cannot be depleted. They are drawn directly or indirectly from the flows of constantly available solar and gravitational energy. Renewable sources include solar, wind, water-related (hydro, tidal, wave) and biomass resources. Geothermal energy is usually classified as a renewable resource however, based on the above definitions, strictly speaking, it belongs to the category of non-renewable resources. This is due to the fact that it is not based on solar or gravitational forces and is depletable (in the sense that as the Earth cools, the amount of geothermal energy will also decrease). However the timescales during which this is likely to happen are so vast that geothermal energy can be considered a non-depletable resource.

From the above section, it could be argued that the main difference between renewable and non-renewable sources of energy is the timescale over which they are available. A further important distinction when examining an energy supply system based on these different types of energy sources is the efficiency of utilisation. Whereas for non-renewable sources, this factor is important from the point of view of sustainability, renewable sources in many ways can be considered “free” and inexhaustible and therefore their utilization efficiency can be deemed irrelevant. What is important in these cases is the commitment of other resources (land, capital, auxiliary energy inputs) to produce the final product, and these can be very important when comparing dissimilar energy supply systems (Perry A.M, Devine W.D, & Reister 1977).

Since the overall aim of EA is to evaluate the total amount of primary energy required to produce a good or service, a "systems approach" is most commonly applied. This involves the creation of an imaginary boundary around the process in question and the measurement of energy flows across the imaginary boundary. This approach leads to the concept of *direct* and *indirect* energy inputs. *Direct* energy inputs are created when heat released by the combustion of fuels passes over the boundary and is used directly in the system. *Indirect* energy inputs are created when fuels are combusted elsewhere to provide the products and services required by the process under consideration within the system boundary. The total amount of energy needed to make one unit of output from the system equals the sum of both the direct and indirect energy inputs. This is referred to as the total energy requirement.

For this current research certain conventions were adopted for the recording of energy units. Specifically, it is recommended that the energy inputs to a system are recorded separately (Perry A.M, Devine W.D, & Reister 1977). The most essential level of disaggregation is that of electrical and thermal inputs. Electrical inputs include all the energy inputs into a system in the form of electricity. These inputs can further be divided into primary and secondary electricity. Primary electricity can be defined as the electricity generated by hydro, wind and nuclear power stations and is regarded as a primary energy form because there are currently no other uses of the energy resource "upstream" of the generation (DTI 2007a). Secondary electricity is the electricity generated by burning fossil fuels. Thermal energy is a generic term for the energy inputs in the form of fossil fuels. Ideally, all forms of energy would be recorded separately (i.e. coal, oil, natural gas etc). However this would prove overly cumbersome for analyses with the number of inputs as those considered in this study.

When discussing the Energy Analysis of energy sources it is particularly important to distinguish between two further terms: the Gross Energy Requirement and the Net Energy Requirement. The Gross Energy Requirement (GER) equals the sum of the direct and the indirect energy used to provide one unit of output plus the energy content of the original source of energy. This includes the total amount of fuel inputs, whether they are directly consumed, transformed into other energy forms or stored in the waste products. It has been argued that this value is especially of interest where the objective of the research is related to investigation of resource depletion (International Federation of Institutes for Advanced Study & IFIAS 1974). The Net Energy Requirement (NER) on the other hand, gives an indication of the amount of energy from other sources required to obtain energy from the particular source in question (Mortimer 1991). This allows the calculation of the energy requirements of a product or service.

The use of the NER in this work, as opposed to the GER, is dictated by the nature of the fuel cycle under investigation. Based on the definition of the GER, it would also be necessary to include the energy content of the spent nuclear fuel, which although categorised as waste, would still be highly radioactive and therefore contain large amounts of energy. However, as there is still potential to use this waste as a fuel source (either through reprocessing or in Fast Breeder Reactors should they become commercially available), defining this energy as “lost” to the system might be seen as unduly disadvantaging the nuclear life cycle. For wind energy however, the same guidelines would require us to calculate the kinetic energy in the wind utilised by a wind turbine, a task both onerous as well as potentially pointless, since wind is not considered a depletable natural resource, especially given current and feasible future rates of “exploitation”. As a result, the use of the GER for the comparison of electricity production from these two energy conversion technologies would lead to the foregone conclusion that wind is sustainable technology, since it does not deplete the natural capital. Even in the case that this metric of sustainability was not the main assessment factor, the energy still embodied in the spent nuclear fuel would be many orders of magnitude above the energy in the waste of any other technology. As such, it is argued that while the GER is the most appropriate metric from the point of view of sustainability and the most applicable when comparing conventional energy conversion technologies (including nuclear), in the case of a comparison between renewables and other conversion systems, the GER does not offer a significant insight. The use of the NER on the other hand permits the evaluation of the energy conversion technologies based on the life cycle efficiency of providing a final product (in this case electricity).

3.5.1.3 Net Energy Analysis

Applying the concept of Net Energy Analysis (NEA) to an energy supply system involves the identification and quantification of the energy flows in society that are required to deliver energy in a particular form, to a given point of use. These energy flows are then compared to the energy converted by the particular system under investigation (Perry A.M, Devine W.D, & Reister 1977). In other terms, NEA compares the energy required for all inputs in developing an energy technology (energy itself, materials and services) with the energy that the technology will eventually produce (Herendeen 1988). NEA was originally concerned with addressing fears that certain technologies could ultimately be net energy users rather than producers. This leads to the conclusion that should such energy systems have to exist without the (fossil fuel based) inputs that provided the initial assistance, the energy expenditure to support them could increase inordinately. Finally, for established technologies and assuming a decreasing amount of readily accessible resources, it was argued that NEA could help identify the limit at which a technology produced less energy than was required to maintain it (i.e. when it became an “energy sink”) (Perry A.M, Devine W.D, & Reister 1977).

3.5.1.4 Unit conventions in NEA

The choice of the units of measurement is not a critical factor in NEA but they need to be consistent throughout. In this work, thermal inputs are measured in Joules (J) and their multiples (kJ, MJ, etc), while electrical energy is measured in Watt-hours (Wh) and their multiples (kWh, MWh, etc). Where conversions between these two units are required, *for the same form of energy,* the standard factor of 1 kWh = 3.6 MJ has been used. Conversions between thermal and electrical energies are calculated using the lifecycle generation efficiency of the conversion technology. In all cases, the electricity conversion efficiency is based on the information calculated using the processes in the Ecoinvent Database. Where the source is the National Grid, the lifecycle electricity generation efficiency has been calculated using the U.K. generation mix for the year 2007, as described in (DTI 2008) and the Ecoinvent database modules. Based on these data sources, this conversion efficiency was calculated to be 35.02 %, or in other words, 1 unit of electricity delivered to the Grid requires an input of 2.86 units of primary energy.

An important caveat needs to be applied at this point to the calculation of grid efficiencies, and the "grid mix" in general. As a matter of course, the energy inputs (and generally the energy expenditures) of future energy technologies have to be modelled on recent patterns of energy production (and use). Naturally the timeframes involved play a significant role in determining the margins of error associated with this approach. Thus, especially in the case of long-term calculations (i.e. longer than the average lifetime of current power plants), the assumption that the current production mix and energy inputs will remain the same into the future, will probably prove erroneous. At the same time however, it is hard to accurately predict what the future energy production mix might look like and therefore any calculations based on predictions are prone to substantial errors. As a result, the background energy system, and accordingly the energy inputs into the future technologies are the average energy requirements for those technologies, calculated *at the margin* of the industrial system that exists currently or in the recent past. The implicit assumption thus is that the energy supply system in question is not large enough to disturb the existing status quo.

3.5.1.5 Cumulative Energy Demand (CED)

One of the main parameters calculated by Net Energy Analysis, is that of the Cumulative Energy Demand (CED). Generally, the CED of a product represents the sum of the direct and indirect energy use throughout the life cycle. In the case where the product under consideration is electricity, the CED would include the energy required to construct and run the power plants, as well as the energy to extract, manufacture, and dispose of the raw and auxiliary materials, including of course the fuel used. Different concepts for determining the primary energy requirement exist. Naturally, for the sum of energies to be representative it is necessary to have a common basis for the accounting for the different fuel types (i.e. 1 MJ of energy delivered from coal is not the same as 1 MJ of energy delivered from natural gas). In order to get round this issue, the CED is defined as the sum of the *primary energies* of the fuels. For CED calculations, it is possible to choose the lower or the upper heating value of primary energy resources (mainly applicable to fossil fuels and biomass). In the case of electricity, when counted as a secondary energy source, the usual method used to calculate the primary energy equivalents is to trace it back to the fuel source used, incorporating the conversion efficiency of the power plant. The situation is less clear in the case of calculating the primary energy equivalent of electricity from nuclear and other sources of primary electricity such as hydro, wind and solar.

There are various conventions to account for the primary energy equivalent. One commonly applied method is that of the "energetic opportunity cost". This opportunity cost is related to the equivalent economic concept and can be defined as the primary energy required to produce the same amount of electricity (that was produced from renewable energy technologies such as wind turbines) in a conventional power station. This opportunity cost is usually only applicable to renewable energy technologies since it is meant to credit these technologies for the energy sources they avoid depleting (since their "fuel" is renewable i.e. non resource depleting). Historically, the energetic opportunity cost has also been applied to nuclear power, as it too avoids the depletion of *fossil-fuels*, which was the primary concern at the time of its inception. However, in this research it is argued that the definition of opportunity cost needs to be re-evaluated so that it encompasses the concept of sustainability. As such, the opportunity cost in this work is used only for systems that are sustainable, in the sense that they are based on non-depletable sources. Nuclear power, therefore, cannot be encompassed in this definition.

The definition of the opportunity cost, however, also entails that a certain conversion efficiency from primary to final energy is assumed, based on the benchmark conventional power system. Usually, the conventional power station is represented by a coal-fired station but occasionally the average national electricity grid in used. Historically, the conversion efficiency has been based simply on the thermal efficiency (of either the plant or the National Grid). However, it is the premise of this work that the life cycle conversion efficiency of the electricity generating system is used instead. This is calculable from the Ecoinvent databases using the conversion efficiency of the U.K. Grid, and has been used in this work. A further discussion of this methodology is presented in the section on energy gain ratios (Section 3.5.1.6).

Other methods for attributing a primary energy equivalent to primary electricity are those used in the Digest of U.K's Energy Statistics (DUKES). In this series of publications, "*the energy value for hydro-electricity is taken to be the energy content of the electricity produced from the hydro power plant and not the energy available in the water driving the turbines. A similar approach is adopted for electricity from wind generators. Nuclear electricity is obtained by passing steam from nuclear reactors through conventional steam turbine sets. The heat in the steam is considered to be the primary energy available and its value is calculated from the electricity generated using the average thermal efficiency of nuclear power stations*" (DTI 2007a).

As can be seen from the above examples, there are a variety of methods for accounting for the conversion of electricity to primary energy inputs and hence there is no agreed standard methodology to calculate the CED. In this current work, the definition and methodology that has been adopted, is the one presented in (Frischknecht, Jungbluth, & et al 2007), which is outlined in the following sections. This methodology is generally accepted as the mainstream approach to Energy analysis and is in-line with that used in the Ecoinvent database, which forms the main input to the models created in this work. Based on this methodology, the characterisation factor for the conversion of energy sources is based on the *upper heating value* of the fossil fuel resources. In the case of nuclear generated electricity, this is converted to primary equivalents based on the lifecycle efficiency of the nuclear fuel cycle (in this case based on the German pressurised reactor fuel cycle) and the "energy content" of the fissile isotopes in the natural uranium extracted from the mines. An analytical description is provided in the methodology outline of the paper (Frischknecht, Jungbluth, & et al 2007). For renewable sources, characterisation factors based on the potential energy of water in a dam (hydro), the kinetic energy in the wind, or the energy in sunlight are used. As a general rule in energy analysis, the energy content of labour in any form is usually excluded from the analysis.

With the parameter of Cumulative Energy Demand thus established, it is then possible to go on to define other parameters which can be used to characterise the energy-related properties of fuel cycles.

3.5.1.6 Energy Gain Ratios

One of the main parameters investigated in any life cycle energy analysis is the Energy Gain Ratio (EGR). The Energy Gain Ratio can be defined simply as the energy produced by an energy supply system (energy output) over its lifetime, divided by the energy required for its construction, continued operation and disposal/dismantling (energy input), but not including the energy content of the fuel:

$$Energy\ ratio = \frac{Energy\ output}{\sum Energy\ inputs} \quad (3.3)$$

Historically, it has been argued by analysts that the Energy Gain Ratio should be considered as a significant parameter in the adoption of one power generating technology over another ((Chapman 1975a),(Tsoulfanidis 1981)). The exact definition of the energy ratio varies widely and depends on the nature of the evaluation. The Energy Gain Ratio has also been defined as the *Energy Yield Ratio* (EYR) by (Wagner & Pick 2004), *Energy Intensity* (Lenzen & Munksgaard 2002) and the *Energy Return on Investment* (EROI) by (Cleveland 2007) amongst many other definitions. It must be noted that each one of these definitions is not completely identical, but what they all have in common is that they serve the purpose of providing a ratio of energy outputs and inputs. In response to the large variety of interpretations concerning the conversion factors for electrical inputs and outputs, and in effect the inherent value of electricity, the International Atomic Energy Agency (IAEA) published a report summarising the best research on nuclear power and addressing the conventions used in Net Energy Analysis (IAEA 1994). The IAEA report highlighted that one of the main problems with defining energy ratios was that there was no single, proper way to add thermal and electrical inputs and subsequently compare them to the electrical outputs of a power station. Thus, it concluded that it would be necessary to define several different energy ratios, each of which is meant to address a different aspect of the energy analysis.

The Energy Gain Ratios defined in this current work are based on the guidelines set out in the IAEA report but have been adapted to better suit the needs of this work and the nature of the aggregation of energy flows, calculated using the Cumulative Energy Demand method (mentioned in previous paragraphs). Specifically, one of the Energy Gain Ratio (EGR1) is simply the ratio of the lifetime *electrical output* (converted to MJ_e) of the station, divided by the NER for the lifecycle of the power plant, measured in primary energy units (MJ_{pr}).

$$EGR1 = \frac{F1 \times E_O}{T_i + Fx \times E_i} \qquad (3.4)$$

where E_o = electrical output (kWh_e)
E_i = electrical input (kWh_e)
T_i = thermal inputs (in MJ_{pr})
F1 = conversion factor between kWh and MJ
F_x = conversion factor of primary to electrical energy units at power plants / the supply grid

Due to the nature of the calculation methodology, the denominator of the energy ratio is already calculated and provided in primary energy units (MJ_{th}) by the impact assessment methodology used in the software. As such, the conversion factor F_x has been defined and used according to the generation efficiencies of the power plants where the electricity is assumed to be generated. An implicit assumption in this definition is that electricity (i.e. the electrical output of the station) has the same "value" as the thermal inputs. This issue has been a point of heated debate ever since the first energy analyses of energy systems were carried out and there is, as of yet, no clear standard as to how to approach the issue.

The alternative energy gain ratio definition also used in this research (termed EGR2), is effectively the same expression as EGR1, with the difference that the "opportunity cost" convention, as defined in Section 3.5.1.5, is applied to the ratio. It represents the conversion of electrical units to their thermal equivalent in primary energy units and is, in effect, a form of the economic "opportunity cost". As stated previously, the purpose of this opportunity cost is to "credit" the renewable energy technologies with the energy they have avoided using, since they do not deplete resources through their operations. As such, this ratio is applied only to the wind farms in this work, and not the nuclear power plant, at the latter is still deemed to be using depletable resources (i.e. uranium). The value of *F2* in the following equation depends on what is considered as the reference energy production system for the definition of the opportunity cost. For the purposes of this research, this reference system has been taken to be the U.K.'s National Grid, using data based on (DTI 2008) and the Ecoinvent database (Dones, Bauer C, Bolliger, & et al 2007).

$$EGR2 = \frac{F2 \times E_O}{T_i + Fx \times E_i} \qquad (3.5)$$

where, as before, the denominator is provided by the software Simapro. However, in this case *F2* represents the "opportunity cost" conversion factor of the primary energy and can be defined as the lifecycle conversion efficiency of the "opportunity cost" system.

3.5.1.7 Aggregation of different energy flows

As can be seen from the description of the above two Energy Gain Ratios, the definition of the conversion factor, *F*, plays an important role in the final outcome. The factor *F*, in effect, describes the relative value of energy in its different forms. Since there is no agreed convention for the aggregation of energy from different sources, it is useful to define different weighting schemes, depending on the aims of the study. (Perry A.M, Devine W.D, & Reister 1977) defined 4 different indexes, some of which have been adapted for this work, and are highlighted in the following sections.

The first method of aggregation is based on the assumption that all energy inputs have the same value. This then leads to a conversion factor of unity, where the conversion factor *Fx* is merely the conversion factor between different energy units of measurement. A second method of valuation splits the energy inputs into thermal and electrical and values the electricity based on the amount of fuels required to generate it. Where the input to secondary electricity is from renewables and nuclear (i.e.

primary electricity), the primary electricity is valued as coming from a conventional power station. Hence this factor effectively values the electricity based on the *conversion efficiency* of the power plants that produced it from primary fossil fuels. The third method of aggregating the energy flows draws a wider boundary round the electricity generation system, encompassing direct and indirect energy requirements. These include the energy required to create and generate the fuels used to generate electricity (in effect the embodied energy of the fuels) as well as the energy requirements for all other materials consumed during the power plant operation. This method however, does not include the embodied energy in the facilities (i.e. the energy required to create the power stations, transmission grid etc). The final method, suggested by (Perry A.M, Devine W.D, & Reister 1977) also encompasses this aspect and therefore is the most complete method from a supply side point of view. This is the approach adopted in the Ecoinvent methodology and used in this work. The conversion factors *F2* and *Fx* used in the ratio EGR2, are of this nature. The factor *Fx* represents the lifecycle energy conversion efficiency of each electricity producer and is effectively embedded in the calculations for the Cumulative Energy Demand described previously. The factor *F2* however, has been defined specifically for the purposes of this work. It is based on the assumption that the electricity is supplied by the U.K. generation mix as outlined in (DTI 2008).

As stated previously, the use of *F2*, in effect, complies with the "opportunity cost" convention since it implies that the electricity generated by the power plant (in this case a wind farm) could have been generated from the grid instead and therefore "credits" the wind farm with the avoided primary energy consumption.

A final point on the aggregation of energy flows is the fact that all the previous definitions are from the viewpoint of the "supply system". Thus they do not take into account the characteristics of the energy end-use devices that can determine the relative "value" of the different forms of energy (Perry A.M, Devine W.D, & Reister 1977). Various attempts have been made to value energy and more specifically electricity based on its end-use (see (Chapman 1974b), (Chapman & Mortimer 1974), (Chapman 1975a)). However, as very little data exists about end-uses of energy, any valuation of energy based on such a criteria will have to be based on explicit and implicit assumptions, leaving it open to debate. Furthermore, as the end product of both energy supply systems under consideration in this work, is the same (i.e. electricity), it was felt that a conversion factor based on end-use would no offer no insight into the comparison of the technologies. The inclusion of end-use as a valuation parameter would only add something in the event that it could be argued that electricity from wind and nuclear power was used differently. However, as both technologies are modelled to be feeding into the same transmission system and supplying the same generic end-user, there were no grounds for such an approach.

3.5.1.8 Energy Payback Period

Another concept used frequently in Energy Analysis, is the parameter called the *Energy Payback Period* or *Energy Payback Time*. The IAEA (IAEA 1994) defines it as:

"…the time necessary for recuperating all the energy consumed in the construction of an energy installation and for its operation during the assumed lifespan of the operation"

This concept is also open to different interpretations for many of the same reasons as the Energy Gain Ratio. Once again the conversion factor for the electrical inputs and outputs influences the payback time significantly, giving ranges for most technologies between months and years, as will also be seen later in this study.

In this report, two Energy Payback times are defined; the "simple" payback time, which is the total energy inputs divided by the annual electrical output;

$$EPP1 = \frac{\sum (T_i + Fx \times E_i)}{F1 \times E_{Annual}} \qquad (3.6)$$

and the "opportunity cost" version, which is applicable to the renewable systems as described above.

$$EPP2 = \frac{\sum (T_i + Fx \times E_i)}{F2 \times E_{Annual}} \qquad (3.7)$$

3.5.2 Greenhouse gas emissions

As stated in previous chapters, the temperature of the Earth is determined by the balance between the energy transmitted from the Sun in the form of sunlight, and the energy constantly re-radiated from the Earth back into space in the form of infra-red radiation. Sunlight passes through the atmosphere and warms the Earth's surface which then in turn warms the atmosphere by convection and the emission of infra-red radiation. This radiation is absorbed by certain trace gases, which are commonly known as greenhouse gases. These gases have the effect of blocking the transition of some the infra-red radiation into space and instead returning it back to the earth's surface. This has as a result the further warming of the planet's surface (HM Goverment 2006). The increased concentration of greenhouse gases in the atmosphere enhances the absorption and emission of infrared radiation. The climatic consequence of these gases is termed the "Greenhouse Effect". The Greenhouse Effect on Earth also occurs naturally, and is desirable for the maintenance of life of the planet. The problem however is that human activities, especially since the Industrial Revolution in the 18th century, have enhanced the natural effect (HM Goverment 2006). As stated in the last report from the Intergovernmental Panel on Climate Change (IPCC), "changes in the atmosphere, the oceans and glaciers and ice caps now show unequivocally that the world is warming due to human activities" (IPCC 2007a).

The main naturally occurring greenhouse gases are water-vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Although water vapour makes the greatest contribution to the greenhouse effect, it has a short lifetime in the atmosphere and its concentration is largely determined by the temperature of the atmosphere and not simply by emission or loss rates. By contrast, the other three gases have relatively long atmospheric lifetimes. Human activities, such as burning fossil fuels, changing land use patterns and deforestation, also affect the quantity of greenhouse gases in the Earth's atmosphere. In addition to the human induced emissions of carbon dioxide, methane and nitrous oxide, industrial activities have generated other greenhouse gases, namely hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. Each greenhouse gas has a different capacity to cause global warming, depending on its radiative properties, its molecular mass and its residence time in the atmosphere. In order to be able to aggregate all the greenhouse gases in one category, an index known as the Global warming potential (GWP) has been introduced. The GWP, defined as the warming influence of a gas over a set time period relative to that of carbon dioxide, is a method that can be used to assess the relative global warming effect of the emissions of different gases over a set time period (HM Goverment 2006). The impact category of the aggregated greenhouse gases is then measured in masses of CO_2 equivalent (CO_2eq).

The reduction of emissions has become a driving force behind almost all policies and is especially relevant to the debate behind the adoption of new energy technologies, both in the UK and internationally. As such, its definition is of primary concern of this study. The method used to estimate the CO_2eq emissions in this research is detailed in (Frischknecht, Jungbluth, & et al 2007) and is based on the method developed by the IPCC, and outlined in (IPCC 2007b). In this work, GWP factors with a timeframe of 100 years were chosen to characterise the gases emitted by the energy supply systems. The list of factors can be seen in the table in Appendix A. A detailed explanation of this method and how the above factors are derived can be found in the Simapro database manual (Goedkoop et al. 2008) and (Frischknecht, Jungbluth, & et al 2007).

3.5.3 Net-Energy Density

Net Energy Density can be used as an indication of how efficiently power stations are utilising their land during their operational lifetime. In order to define the Net Energy Density of a technology, it is first necessary to define the technology's *Spatial Footprint.* This can be defined as the total land consumption required during the lifetime of the fuel chain. The values for land-use are derived from data provided with the material databases in SimaPro, as well as from a number of research articles and various reports published by governments and organisations. A general definition of the energy density is the fraction of a power plant's net energy divided by land used over the lifetime of the plant. An important factor in the definition of energy densities is the application of temporal and spatial dimensions. As a result, it is not only necessary to calculate the net energy balance, but also to multiply the land consumption by the number of years that it is required for electricity production:

$$e = \frac{Energy\,output - Energy\ inputs}{(land\ use) \times operational\ lifetime} \cdot \left(\frac{GWh\ lifetime}{km^2 \times years} \right) \tag{3.8}$$

This is especially important in the case of the nuclear fuel cycle, as the storage of waste will outweigh the production lifetime by hundreds of years. In this case, it is necessary to multiply the required land for waste storage with a separate value from that of the land required during electricity production, as can be seen in Equation 3.9:

$$e_{nuclear} = \frac{Energy\,output - Energy\ inputs}{(land\ use)_1 \times oper.\ lifetime + (land\ use)_2 \times waste\ storage\ lifetime} \cdot \left(\frac{GWh\ lifetime}{km^2 \times years} \right) \tag{3.9}$$

A power station with a high Net Energy Density can be said to be producing a high output for the given land required to provide this energy output and vice versa. This parameter is of special importance, when there is a short supply of land which can be used for energy production, or when a technology is highly dependant on the land area for the production of electricity (e.g. electricity from biomass).

It should be pointed out that in both the case of the nuclear power lifecycle and the wind lifecycle, the energy inputs are to be converted from *primary energy* terms to electrical energy using the lifecycle National Grid efficiency. This then allows the deduction of these energy inputs from the electrical output of the power stations.

3.5.4 Material requirements

An issue that has become increasingly debated with the projected growth in nuclear and renewable power, is the quantity of material resources required to deploy each technology in question. The subject has been investigated by different researchers, as can be seen by the works of (Grüzenich & Mathur 1998),(White & Kulcinski 2000), (Voorspools, Brouwers, & D'haeseleer 2000) and (Wagner & Pick 2004) among others. In these works, the quantities of building materials for different conventional and renewable energy technologies have been aggregated and normalised either by their rated capacity or by the output of the stations throughout their lifetimes. This approach is indirectly connected to the assessment of the environmental impacts that these technologies have, while it can also serve to identify potential supply chain problems by highlighting how the mass deployment of a technology might affect demand for certain materials.

Recently, the National Renewable Energy Laboratory (NREL), in its report on the impact of a high percentage penetration of wind energy (Laxson, Hand, & Blair 2006), identified several materials that could provide limiting factors in the large-scale uptake of the technology. Specifically, it identified steel, fibreglass, rare-earth magnets and copper supplies as facing potential problems. At the same time other commentators have focused on the supply chain problems of specific components rather than the raw materials. Work has been carried out by the Department of Energy (DOE) in the U.S. (DoE 2005) on the deployment of nuclear power and highlighted that certain specific components that are required in nuclear reactors could potentially become limiting factors in the expansion of nuclear power. For the wind industry the EWEA also published an article (Aubrey 2007), highlighting the strain on the wind turbine supply chain. The article cited the lack of bearing and gearboxes, as well turbine blades as limiting factors in the continuing growth of wind energy and went on to suggest that this was caused by the price and availability of raw materials. Specifically, it pointed out that the lack of steel (used in most structural components), copper (used in generators and cables) and materials for the manufacture of blades, were creating bottlenecks.

In order to highlight the issues outlined above, it was decided to illustrate the material requirements for each type of power plant under investigation. The decision was made to focus on certain materials that were common to both wind and nuclear power, and that were highlighted in the above sources. The material quantities were then normalised by the energy output over their lifetime to provide a common basis for comparison. It must be noted that the material requirements calculated for this parameter are the direct material requirements (i.e. associated with the construction and operation), and therefore do not include the requirements of the supporting systems (i.e. the impact category does not include the materials used to create the vehicles, manufacturing facilities etc). In order to include that level of detail, while still providing meaningful results, a separate impact category which looks at the depletion of major resources has been created. The resulting indicator is described in the next section.

3.5.5 Resource Depletion

Apart from the direct material requirements, from a lifecycle perspective, the mineral requirements for each energy supply system have been assessed. The depletion of natural resources is an issue that was originally a part of the scope of Energy Analysis (as can be seen by the guidelines set out by (International Federation of Institutes for Advanced Study & IFIAS 1974) and (Perry A.M, Devine W.D, & Reister 1977)), but later on was encompassed in the broader objectives of the Life Cycle Assessment (LCA) methodology. The method used in the current work is based on one of the methods developed for LCA, but adapted to the scope of this work. The substances under investigation have been adapted from the “EDIP/UMIP resources only” method (Goedkoop, Oele, Effting, & PRe' Consultants 2008), where the resources are given in individual impact categories, on a mass basis of pure resource (i.e. 100% metal in ore, rather than ore). The resources were chosen based on research on reserves originally carried out in the 1990s, as quoted in (Karen Leffland & European Environment Agency 1997), as well as work carried out by the Material Innovation Institute (Wouters & Bol 2009) and BP (BP 2010). From those works, a table of the main natural resources considered and their reserves is presented below:

Resource	**Reserves**		**World reserves life index (1990)**	**World reserves life index (2004)**	**World reserves life index (2009)**
		units	**years**	**years**	**years**
Oil	181,700 [2]	10^6 tonnes	43	-	45.7
Coal[1]	826,001 [2]	Mtoe	172	-	119
Natural gas	187,490 [2]	10^9 m^3	61	-	62.8
Iron	80,000 [3]	10^6 tonnes	118	64	-
Aluminium	23,000 [3]	10^6 tonnes	195	147	-
Zinc	220 [3]	10^6 tonnes	20	24	-
Copper	470 [3]	10^6 tonnes	36	32	-
Nickel	62 [3]	10^6 tonnes	52	44	-
Manganese	380 [3]	10^6 tonnes	86	n/a	-
Lead	67 [3]	10^6 tonnes	21	21	-
Tin	6.1 [3]	10^6 tonnes	27	24	-
Water	-	km^3	Infinite	Infinite	Infinite

[1] bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal.

[2] Based on 2009 data.

[3] Based on 2004 data.

Figure 3.5 Reserves and scarcity for selected materials

3.5.6 Water Consumption

The generation of electricity is a process that is currently heavily dependent on the use of water. It has been stated that "in terms of conserving water, a slight reduction in water consumption in the electricity sector will far outweigh other modes of saving […] in the household sector."(Inhaber 2004). Conventional thermoelectric plants use water mainly for cooling purposes. However, they also use water for the operation of flue gas desulfurization (FGD) devices, ash handling, wastewater treatment, and wash water (Feeley III, Skone, Stiegel, McNemar, Nemeth, Schimmoller, Murphy, & Manfredo 2008). Some commentators have supported the view that water usage is only an issue for thermoelectric power plants, while renewables not only do not consume water, but can be "implemented in such a way that they actually benefit water supply."(von Uexküll 2004). However, more recently, work by (Inhaber 2004) has supported the view that "renewable energy systems, both present and future, can withdraw considerable water when the entire energy cycle is considered". The same work then goes on to state that renewables can have water use (per unit energy output) comparable to conventional power systems, especially when the entire life cycle is considered.

When discussing the use of water in industrial processes (and especially in electricity generation) it is important to distinguish between *water withdrawal* and *water consumption*. Water withdrawal represents the total water taken from a source, while water consumption represents the amount of water withdrawal that is not returned to the source (Feeley III, Skone, Stiegel, McNemar, Nemeth, Schimmoller, Murphy, & Manfredo 2008). Water withdrawal for energy production is generally much greater than water consumption. Water consumption for thermoelectric plants is of the order of 2% of water withdrawn (Inhaber 2004).

In this work water consumption values are the ones considered, because water consumption is deemed a better indicator of sustainability as it represents the water "lost" in the process (Evans, Strezov, & Evans). The values for the water use are taken mostly from the Ecoinvent database, except where otherwise stated. The aim of the parameter is to illustrate the relative water use of the two power plants under consideration. The unit of measurement is taken to be m^3 / kWh_e produced.

3.5.7 Avoided Carbon Dioxide emissions

As both wind and nuclear power are considered to have lower carbon dioxide emissions than conventional generation, the view can be supported that if these two technologies displace the electricity produced by conventional generation, then they also displace the emissions that would have been produced. This can happen because electricity from renewables is given priority access to the national grid (under the Renewables Obligation), while nuclear always runs as "baseload", and therefore provides electricity that would otherwise have to be provided by large gas fired or coal-fired plants. The specific types of fossil fuel-fired power units that will be displaced by wind or nuclear generation, however, vary with a variety factors, including the time of day, month and year as well as the relative prices of fuels used in generation. The quantity of emissions displaced also varies with the age of the fossil fuel-fired units, as well as their relative levels of efficiency and pollution control. Thus, emissions from displaced electricity depends on the dynamic interaction of the electrical grid, emission characteristics of the grid connected electricity generators, the loads on the system, market factors as well as a variety of regulatory factors.

In order to estimate the "avoided" emissions it is necessary to define a baseline scenario that represents the emissions that would have been generated, if the electricity had not been generated by a near zero carbon technology. The theoretical framework has been set out in (World Resources Insitute & Breckhoff 2007) and adapted for this work. Once this baseline scenario is defined, to calculate the exact amount of carbon dioxide emissions that are avoided by the accepting near zero carbon electricity into the electricity grid, it is necessary to subtract the actual lifecycle CO_2 emissions from the generation of this electricity from estimated "avoided" CO_2 emissions from the baseline scenario. The emissions from the baseline scenario are estimated by determining the emissions from the sources of electricity that are assumed to be displaced. An important assumption of this approach to determining the emissions from the baseline scenario, is that the generation of near zero carbon electricity not only displaces the electricity (and hence the emissions) from existing power plants but can also avoid the need for the construction of other new power plants. To calculate the avoided emissions thus, it is necessary to define two separate categories of emissions; the displaced emissions from already operational plants, defined as the Operating Margin (OM) and the emissions displaced from the avoidance of building new power plants, known as the Built Margin (BM).

The baseline emissions are estimated by:

1. Determining how the near-zero carbon technology affects the OM and BM
2. For each margin (i.e. OM and BM), determining the appropriate emission factor and
3. Calculating the overall baseline emissions rate

The formula for calculating the baseline emissions factor $EF_{baseline}$ can be seen below:

$$EF_{baseline} = w \times EF_{BM} + (1 - w) \times EF_{OM} \qquad (3.10)$$

where EF_{BM} is the emissions factor for the Built Margin, EF_{OM} is the emissions factor for the Operating Margin and w is the weighting of the BM.

The weighting factor w acts as an indication of where the avoided generation (and hence emissions) would have originated, had it not been displaced by the near-zero carbon electricity. The weighting factor accepts values between 0 and 1; a value of 1 indicates that the low carbon energy supply system is displacing an alternative form of capacity addition (i.e another new power plant), whereas a value of 0 indicates that the energy supply system under consideration is only displacing the generation from existing power plants and has no effect on the addition of new capacity. Once the emissions factor for the baseline case has been estimated with the above equation, the total baseline emissions are then calculated by multiplying this factor by the total electricity generated by the near zero carbon technology.

Built Margin (BM)

In most cases, near-zero carbon grid connected projects are capable of meeting the supply networks need for new capacity. This means that through the implementation of the project, there is no need for alternative generation to be built as well, or else it does not need to be as large in capacity. This incremental new capacity that is avoided by the project's implementation is known as the Built Margin. The BM is generally calculated by looking at the emissions rates of recent capacity additions as well as planned and "under construction" facilities, as these indicate what would have been built instead of the project.

Operating Margin (OM)

The OM represents the electricity and associated emissions from already operating power plants that are curtailed as a result of the project's implementation. The OM factor can be estimated using a variety of methods, each one with a different level of data requirements. Theoretically, these methods require the identification of which plants are operating "at the margin" (i.e. are the last to be switched on to meet demand and the first to be turned off) during the time of operation of the near-zero carbon power plant. Which plants are at the margin vary considerably with a range of temporal, economic and climatic factors.

As part of this work, two new parameters are introduced, the Carbon Dioxide Gain Ratio (CDGR) and the Carbon Dioxide Payback Period (CDPP). Both of these parameters are directly related to the estimation of the avoided emissions described above and are explained in more detail in the following sections.

3.5.7.1 Carbon Dioxide Gain Ratio (CDGR)

The Carbon Dioxide Gain ratio reflects the same considerations as its energetic equivalent, the Energy Gain Ratio described previously. It represents a measure of how many times more carbon dioxide is avoided compared to the carbon dioxide emissions embodied in its lifecycle.

$$Carbon\ Dioxide\ Gain\ Ratio = \frac{Avoided\ CO_2\ emissions\ from\ operation}{Embodied\ CO_2\ emissions\ in\ the\ lifecycle} \quad (3.11)$$

3.5.7.2 Carbon Dioxide Payback Period (CDPP)

Once the avoided carbon dioxide emissions have been calculated, it is possible in similar fashion to the Energy Payback Period, to estimate the time required for the power plants to displace the same quantity of CO_2 emissions as those created by their whole lifecycle operation. This has been termed the Carbon Dioxide Payback Period and is defined as:

$$Carbon\ Dioxide\ Payback\ Period = \frac{Total\ CO_2\ lifecycle\ emissions}{Annual\ avoided\ CO_2\ emissions\ from\ operation} \quad (3.12)$$

3.6 Summary of methodology

In the above sections, the methodology used throughout this work is highlighted. It can be seen that the methodology presented here covers a wide range of impact categories, in order to represent as clearly as possible, all the aspects of the fuel cycles under investigation. The scope of this methodology is such that it seeks to cover a variety of topics that are already or are likely to become important in the near future, providing a common basis of comparison for two fuel cycles based on different principles.

4. Introduction to nuclear and wind systems

4.1 Introduction

The aim of this chapter is to provide background material and theory regarding the two energy systems being investigated and presented in this thesis. Both energy supply systems are comprised of various and distinct stages and underpinned by complicated theory, highly specific to each system in question. The following sections aim to provide a grounding in the underlying principles of both nuclear and wind power systems.

4.2 Nuclear power systems

Nuclear power is characterised by a complicated chain of stages that must be undertaken before it is possible for the power station to produce electricity. Furthermore, during and at the end of operation, many different procedures are required to complete the lifecycle. The following sections provide an introduction and detailed overview of these stages.

4.2.1 The nature of the nuclear power cycle

Of all the fissile materials originally created with the birth of the Earth, only uranium and thorium are still present in a natural form in the planet's crust, since their half lives are of the order of billion years. It is estimated that one tonne of rock and soil contains approximately 1- 5 g of uranium and 3 -20 g of thorium. The ocean is estimated to contain 3 mg of uranium per tonne of sea water (ISA 2006). The most important of the two fissile materials for energy production at this moment in time is uranium. It exists in nature in the form of at least three isotopes, with mass numbers of 234, 235 and 238 (^{234}U, ^{235}U and ^{238}U). The proportions of these isotopes in the element are approximately 0.006%, 0.72% and 99.28% respectively. From this it can be seen that the most abundant isotope is ^{238}U, although it is mainly the ^{235}U isotope that is used in the nuclear fission process.

Nuclear fission is the splitting of the nucleus of an atom into parts (lighter nuclei) often producing free neutrons and other smaller nuclei. These free neutrons then collide with other atoms and so on, creating what is known as a chain reaction. Fission of heavy elements is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). The device in which fission energy is released in a controlled manner is known as a nuclear reactor. Most of this energy is released in the form of heat, which in turn is used to produce steam. From this point onwards, a nuclear power plant produces electricity in much the same way as conventional power stations (i.e. the steam drives a turbine which is connected to a electricity generator)(Rahn et al. 1984).

4.2.2 Reactor types and operation

In a nuclear reactor neutrons are used to split uranium nuclei in a process known as nuclear fission. The fission of the nuclei releases energy in the form of kinetic energy of the fission particles (mainly neutrons), as well as in the form of heat and radiation. The neutrons produced by fission are traveling at great speeds, and in most reactors, are deliberately slowed down by a material known as a moderator. Slow neutrons are much more likely, when they collide with the nuclei of U-235, to cause fission and keep the reaction going. A moderator is composed of light atoms and the materials most commonly used are carbon in the form of graphite, and water. For more precise control of the chain reaction, control rods are inserted into the core of the reactor. When inserted into the reactor chamber, they absorb neutrons and slow down the reaction – pulled out they allow it to speed up again. Thus the level of insertion can control the chain reaction in the nuclear reactor (Cameco 2006).

Fission occurring in the reactor results in the generation of enormous amounts of heat. The energy is transformed to heat, which in turn is used to heat the water in the reactor. The steam that is thus generated drives a turbine connected to a generator, which converts the energy to electricity. After passing through the turbine the steam is condensed to water in a condenser which operates through heat exchange with a cooling agent (usually seawater). After filtering, the water is recirculated to the reactor (Vattenfall AB 2004a). The reactor is surrounded by shielding, which is typically made of steel and concrete about two metres thick, and forms an outer casing that prevents radiation from escaping into the environment.

The previously described general process can be achieved in many different ways. The production of electricity can be achieved with a variety of fuels, moderators and coolants thus leading to a large number of potential nuclear reactor designs. Following experimentations with different approaches after the Second World War, nuclear designs have matured and coalesced into certain general reactor categories which were then developed on a commercial scale. The six main reactor types commercially available today are described analytically in (IET & Institution of Engineering and Technology 2008), and are summarised in the following sections:

MAGNOX Reactors

The MAGNOX reactors belong to some of the earliest reactor designs. They are gas cooled with carbon dioxide and use graphite as the moderator. MAGNOX reactors are thus named because of their use of a magnesium alloy as the cladding for the fuel rods, while the fuel rods themselves were made of natural uranium. These reactor types were originally built in the UK during the period of 1956 to 1971, but have since been superseded.

Advanced Gas-Cooled Reactor (AGR)

In order to achieve better cost effectiveness of the above reactor type, it was necessary to increase the operational temperatures of the reactor. This in turn necessitated a change in the type of fuel used (from natural to uranium oxides) as well as a change in the cladding material to stainless steel. While the moderator was still graphite there was an increase in the gas coolant temperature. The resulting design was named the AGR.

CANDU

The CANDU reactor was designed in Canada and is the only commercial design to use heavy water as a moderator. The reactor uses un-enriched uranium as a fuel and pressurised heavy water to transmit the reactor’s heat to conventional heat exchangers that heat water for a conventional steam cycle.

The use of higher levels of uranium enrichment allow for the use of stronger neutron absorbing material, and hence the use of ordinary water as moderator and cooling medium. There are two major reactor designs based on this principle, which originated from US military technology, as well as designs from other countries, namely Russia.

Pressurised Water Reactor (PWR)

The Pressurised Water Reactor (PWR) uses enriched uranium dioxide as a fuel and zirconium based cladding for the fuel rods. In a PWR, water is kept under pressure to keep it from reaching boiling point and is subsequentely pumped through a closed system of pipes called the primary circuit, round the core. Heat from the primary circuit is then used to increase the temperature of water kept in a separate circuit called the secondary circuit. The water in this secondary circuit is allowed to boil and it is the steam from this that is used to turn a turbine, in the way of a conventional steam cycle. The water in the primary circuit is then re-circulated to the core (Cameco 2006b).

Boiling Water Reactor (BWR)

The second type of reactor based on the use of ordinary water, the Boiling Water Reactor, allows the water to actually boil as it passes the reactor core, therefore removing the need for a separate steam generator. The drawback of this method means that parts of the steam circuit and turbine are then contaminated which leads to the need for increased shielding.

RBMK Reactor

Around the same time that the UK was developing the MAGNOX reactor design, the Soviet Union developed a water-cooled, graphite moderated design, known as the RBMK reactor. The reactor used water to remove the heat from the reactor by allowing it to boil the coolant which in turn drove the steam generators. The whole cycle had to be shielded in order to prevent exposure to the radioactive steam. The Chernobyl reactor in the Ukraine was of this design.

4.2.3 Commercial nuclear power in the UK

The United Kingdom played an important role in the early stages of the development of civil nuclear power. While in the post- war years, the U.S.A focused mainly on the development of nuclear reactors for marine propulsion, the U.K. started operating the world’s first full scale civil reactor, at Calder Hall in 1956, producing 196 MWe of power. This initial reactor was then followed by a planned fleet of up to 2000 MWe of Magnox reactors, while steps were taken to create a fast-breeder reactor program, which would increase the utilisation of uranium (WNA 2009).

Following these initial steps, however, nuclear development in the country slowed, as reports in 1988 raised concerns over the cost-effectiveness of nuclear power and then while in 1989 the privatisation of the U.K.’s electricity sector damped enthusiasm for the development of further reactors. As can be seen below in Table 4.1 (compiled from (WNA 2009) and (IAEA 2008)), a large number of commercial reactors were built and operated in the U.K. over the last 50 years. while over 18 reactors have since been decommissioned since 1980. However, it is also important to note that out of the reactors still operating, all but one (Sizewell B) will be decommissioned by 2023.

Reactors	Type	Net capacity each	Start Operation	Expected shutdown
Oldbury 1 & 2	Magnox	217 MWe	1968	Dec 2010**
Wylfa 1 & 2	Magnox	490 MWe	1971-72	Dec 2010**
Dungeness B 1 & 2	AGR	545 MWe	1985-86	2018
Hartlepool 1 & 2	AGR	595 MWe	1984-85	2014
Heysham 1 & 2	AGR	615 MWe	1985-86	2014
Heysham 3 & 4	AGR	615 MWe	1988-89	2023
Hinkley Point B 1 & 2	AGR	620&600 MWe*	1976-78	2016
Hunterston B 1 & 2	AGR	610 & 605 MWe*	1976-77	2016
Torness 1 & 2	AGR	625 MWe	1988-89	2023
Sizewell B	PWR	1196 MWe	1995	2035
Berkeley 1 & 2	Magnox	138	1962	1988-89
Bradwell 1 & 2	Magnox	123	1962	2002
Calder Hall 1-4	Magnox	50	1956-59	2003
Chapelcross 1-4	Magnox	49	1959-60	2004
Dungeness A 1 & 2	Magnox	225	1965	2006
Dounreay DFR/PFR	FBR	14/234	1962/75	1977/1994
Hinkley Pt 1 & 2	Magnox	235	1965	2000
Hunterston A 1 & 2	Magnox	160	1964	1989-90
Sizewell A 1 & 2	Magnox	210	1966	2006
Trawsfynydd 1 & 2	Magnox	196	1965	1993
Windscale	AGR	28	1963	1981
Winfrith	SGHWR	92	1967	1990

* running at 70% power indefinitely.

** NDA has been examining possible 2-year life extensions, and has announced that Oldbury will continue for about two years beyond its scheduled December 2008 shutdown date.

Table 4.1 Reactors in the United Kingdom

The last commercial nuclear reactor to be built in the United Kingdom was at Sizewell in Suffolk, in the late 1980s. Sizewell "B", as it became known, was based on a "Generation II" Pressurised Water Reactor (PWR) and was the only reactor of its kind to be built in the UK. It was finally commissioned in 1995, after years of delays and extensive public enquiries. However, the concerns raised by the public debate over the safety and financial viability of nuclear power, combined with opposition of public opinion after the Chernobyl incident, ultimately led to the demise of the British nuclear programme. Sizewell B was designed by the U.S. company Westinghouse Electric, although changes were made to the original design to meet UK regulations. Current proposed designs belong to the so-called "Generation III+" reactors, which are a development of any of the Generation II nuclear reactor designs (such as Sizewell B) but which incorporate evolutionary improvements developed during the lifetime of the previous reactor designs, such as improved fuel technology, passive safety systems and standardized design which include advanced passive safety features. It is claimed that Generation III+ reactors can maintain the safe state without the use of any active control components. Due to the inactivity in the nuclear construction sector since the construction of Sizewell B, domestic companies in the UK have little recent experience in the design and commissioning of new nuclear power plants. As a result, any new nuclear build will most likely have to be undertaken by companies from abroad. In early 2008, the Health and Safety Executive has shortlisted 4 designs for possible new build in the U.K; two PWRs, the Advanced Passive (AP) series developed by Westinghouse and the European Pressurised Water Reactor (EPR) offered by AREVA of France (Sustainable Development Commission 2006a), a CANDU reactor (ACR-1000) offered by the Atomic Energy of Canada (AECL) and a Boiling Water Reactor (BWR), offered by the G.E.-Hitachi consortium.

In June 2008, it was announced that the CANDU reactor had officially been withdrawn from the assessment process, due to the AECL's decision to concentrate on their already established markets (AECL 2008). Each of the reactor vendors attempted at the same time to team-up with an electricity utility to further demonstrate their ability to implement a construction program. One of the main European utilities, EDF (Électricité de France) expressed an interest in combining with French/German manufacturer AREVA, as did other major utilities interested in new nuclear build. The withdrawal of the only CANDU reactor meant that the only designs left for consideration were 2 PWR designs and a BWR. For the purposes of this study, it was decided to base the nuclear reactor model on the PWR design. Firstly, it was felt that the "endorsement" shown to the PWR design by major utilities, as well as the geographical proximity of the manufacturer/vendor (in the case of AREVA) could swing the decision in favour of this reactor type. Also, the historical ties between the British nuclear industry and Westinghouse (the company used to be owned by British Nuclear Fuels Ltd. before being sold to Toshiba Group in 2006) could also influence the choice of reactor type. Finally, worldwide, PWRs outnumber BWRs by almost 3 to 1 (WNA 2008a). As such, it was felt that the choice of the Pressurised Water Reactor would be more likely to be relevant to future developments in the UK and international nuclear arena.

4.2.4 Uranium Supply

Uranium is classified as a metal and forms a constituent of most rocks in the Earth's crust. It is about as common as zinc or tin and is most commonly found with deposits that contain phosphates, arsenates and vanadates (Rahn, Adamantiades, Kenton, & Braun 1984). An orebody is an occurrence of mineralisation from which the metal is *economically* recoverable. Therefore, the definition of orebody is relative to both costs of extraction and market prices. Measured resources of uranium, the amount known to be economically recoverable from orebodies, are thus also relative to costs and prices. They are also dependent on the intensity of past exploration effort. Changes in costs or prices, or further exploration, may alter measured resource figures markedly (WNA 2008b).

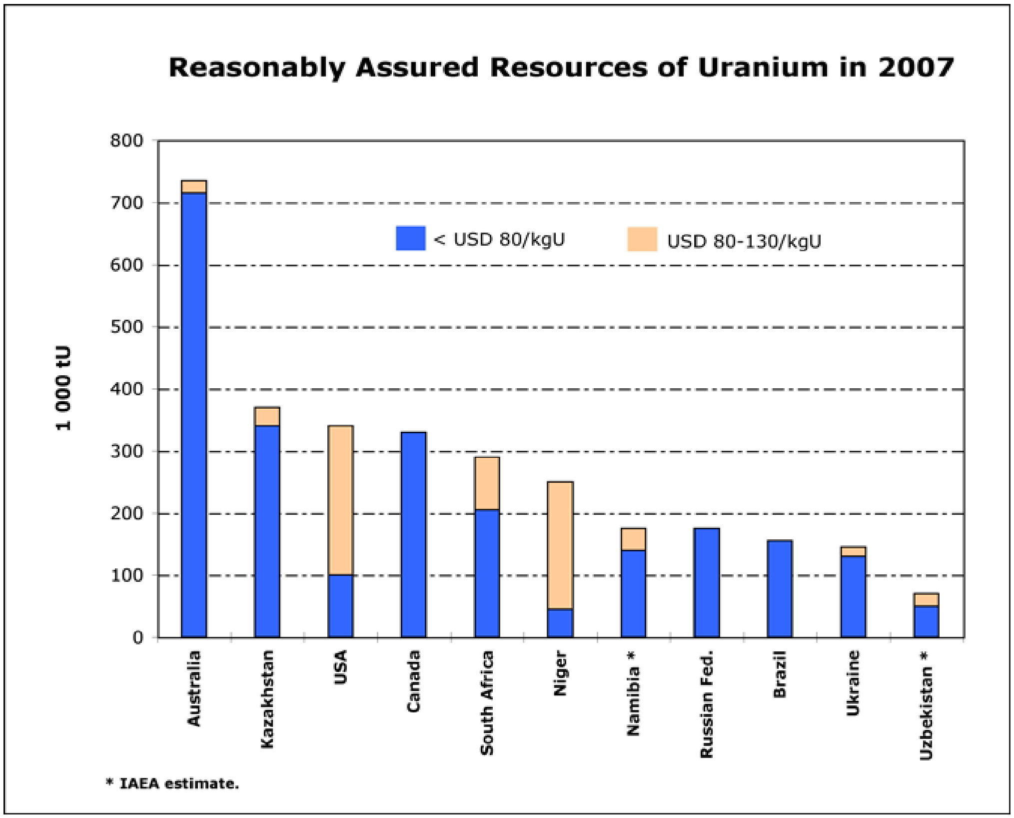


Figure 4.1 Reasonably Assured Resources plus Inferred Resources, to US$ 130/kgU

Figure 4.1, using data from OECD NEA & IAEA, *Uranium 2007: Resources, Production and Demand*, as reported in (WNA 2008b), gives an indication of available resources. It is estimated that the current consumption of uranium, worldwide, is in the region of 65,000tU/yr. Thus, based on current uranium spot prices and the use of current reactor technology, present measured resources are enough to last 80 years. However, many organisations feel that, assuming an increase in the rate of exploration (that until recently had stagnated) and an increase in fuel prices which in turn would make more uranium deposits economically recoverable, supplies of uranium could last 200 years based on current consumption levels (WNA 2008b). A study by the International Atomic Energy Agency, looking into the supply of uranium out to 2050, concluded that provided exploration programs were initiated in a timely manner, and sufficient deposits were found, uranium supplies could be guaranteed at sufficiently low prices to satisfy demand in all but their high nuclear growth projections. In the case of their high growth rate scenario, it was stated that high cost conventional and unconventional sources would have to be brought into play to meet demand. The report also goes on to point out that a reduction of the tails assay during the enrichment process could also have a significant impact on prolonging uranium supplies (IAEA 2001).

EURATOM, the institution responsible for the regular and equitable supply of nuclear fuels for European Community users, claimed in their 2006 Annual Report that "*Uranium resources are not the limiting factor for increasing [nuclear fuel] production over the medium term. Known and proven resources exist for a substantial increase or sustaining the current rate for decades*" and also went on to echo the IAEA's assertion that "more focused exploration is expected to increase available resources over time, since there has been very little exploration from the mid 1980s until recently, and exploration methods have improved significantly over that period" (EURATOM 2007). Finally it stated that any difficulties in the short term of increasing production were more likely to be related to regulatory delays and the lack of infrastructure. However it also conceded that geological challenges and technical issues were to blame.

A study carried out by the Sustainable Development Commission in the U.K., on the other hand took a more pessimistic view (Sustainable Development Commission 2006e). The work in the report was based mainly of IEA and IAEA figures, and argued that assuming that no new mines would become operational in time, existing mines and other infrastructure (such as enrichment plants) would suffer shutdowns, secondary uranium supplies would dry up and a higher increase in demand than predicted would occur, thus resulting in a shortfall in most projection scenarios over the short term. However, even the Sustainable Development Commission accepted that although there are considerable risks of not meeting demand, provided considerable effort is expended in time, supply-side problems could be avoided.

From all the above reports, it can be strongly argued that the potential scarcity of uranium supplies appears to be more a matter of lack of adequate preparation for the increase in demand rather than an actual physical scarcity of uranium. Given of course that all the projections are based on demand assumptions that might or might not materialise, the subject of the availability of uranium supplies will remain a theoretical debate for the immediate future.

4.2.5 "Front End"

All the activities preceding the generation of electricity at the nuclear power plant are termed as the "front end" of the nuclear fuel cycle. These activities include the extraction and refinement of uranium, the enrichment of the product and the fabrication of the fuel rods for use in the reactor core. The following sections give an overview of these stages and describe the modelling within.

4.2.5.1 Uranium mining and milling

Uranium ore is extracted in one of three ways depending on the characteristics of the deposit. Uranium deposits that are close to the surface can be recovered using an open pit mining method, whereas in the case of deposits located deep in the ground, underground mining methods are used. In some circumstances the ore may be mined by in situ leaching. This process involves dissolving the uranium while still underground and then pumping the uranium-bearing solution to the surface. A brief description of each method follows below (Cameco 2006b):

Open-pit mining

Uranium deposits that are located near the surface, generally less than 100 metres deep, are typically extracted by the open pit mining method. Open pit mining begins by removing overburden and then a pit is excavated to access the ore. To mine each bench, holes are drilled into the rock and loaded with explosives, which are detonated to break up the rock. The resulting broken rock is then hauled to the surface in large trucks that carry up to 200 tonnes of material at a time.

Underground mining

When an orebody is located more than 100 metres below the surface, underground mining methods are necessary since it is uneconomic to mine by open pit. Entry into underground mines is gained by digging vertical shafts to the depth of the orebody. Then a number of tunnels are cut around the deposit. In most underground mines the ore is blasted and hoisted to the surface for milling

In situ leaching (ISL)

In a few places geological conditions allow uranium to be dissolved directly by pumping weak acid underground, bringing it back to the surface, and extracting the dissolved uranium. With this in situ leach (ISL) process there is limited surface environmental disturbance. The surrounding rock remains in place while the dissolved uranium is pumped to the surface then circulated through a processing plant for extraction.

After mining, ore is usually transported to a nearby mill for processing. The uranium ore is a mixture of minerals and waste and as such, is firstly crushed, unless it is in a solution already, and treated with acid to separate the uranium metal from unwanted rock. It is then purified with chemicals to selectively dissolve the uranium. The uranium-rich solution is then chemically separated from the remaining solids and precipitated out of the solution. Finally, the uranium is dried. The resulting powder is uranium oxide concentrate, U_3O_8, commonly referred to as yellowcake because of its yellow colour.

Following crushing, the ore is ground and processed through a sulfuric acid leach to recover the uranium. The mixture is then separated from the barren tailings and the uranium is removed using kerosene with an amine as a solvent. The solvent is then stripped, using an ammonium sulphate solution and injected gaseous ammonia. Yellow ammonium diuranate is then precipitated from the loaded strip solution by increasing the alkalinity of the solution, and then removed by centrifuge. Finally, in a furnace, the diuranate is converted to uranium oxide product (U_3O_8).

4.2.5.2 Conversion

Once the ore has been processed, the concentrate (yellowcake) needs to be purified before it can be enriched. Two commercial methods for purification are available: one based on solvent extraction of uranyl nitrate (commonly known as the ‘wet’ method) and the other based on fluoride volatility (‘dry’ method). In the ‘wet’ method, the uranium concentrates are first purified by solvent extraction and then converted either to uranium dioxide (UO_2) or uranium hexafluoride (UF_6). In the ‘dry’ route, the process is inverted with the concentrate first being converted to UF_6, and then purified.

4.2.5.3 Enrichment

Uranium found in nature consists largely of two isotopes, U-235 and U-238, with U-235 being the main fissile isotope of uranium. The goal of enrichment is to increase the fissionable ^{235}U to around 2-5% from 0.71% which occurs in natural uranium. The remaining 99.3% is mostly the U-238 isotope which does not contribute directly to the fission process. Uranium-235 and U-238 are chemically identical, but differ in their physical properties, particularly their mass. The U-235 atom has an atomic mass of 235 units while the U-238 nucleus has three more neutrons than U-235, and therefore has a mass of 238 units. The difference in mass between U-235 and U-238 allows the isotopes to be separated and makes it possible to increase or "enrich" the percentage of U-235 (WNA 2008c). Hence, enrichment involves the altering of the isotope ratios of uranium and this is usually done by isotope separation. Two methods are widely used to enrich uranium in the world today: the gaseous-diffusion method (abbreviated to diffusion method) and the gas-centrifuge method.

The diffusion method for the separation of isotopes makes use of the fact that gases of different molecular weights diffuse through a porous barrier at different rates. The lighter isotopic molecules diffuse through such a barrier more readily than the heavier ones, resulting in a partial separation of isotopes. The gas that passes through the barrier will therefore be richer in the lighter isotopes while the remaining gas will contain more of the heavier isotopic form. The gas-centrifuge method is based on the fact that if a gas containing isotopes of different molecular weights is subjected to centrifugal forces, the heavier molecules will move towards the periphery whereas the lighter ones will stay closer to the centre (Glasstone & Sesonske 1981).

To obtain the desired enrichment and quantity, plants are designed as a series of cascades, each containing multiple units. At each stage, the enriched uranium is fed to a higher enrichment cascade, while the depleted product goes to a lower one. The capacity of enrichment plants is measured in terms of 'separative work units' or SWU. The SWU is a complex unit which is a function of the amount of uranium processed and the degree to which it is enriched and the level of depletion of the remainder (i.e. depleted uranium). The SWU is best thought of as the amount of energy required to take 1kg of uranium from one enrichment to another (Rahn, Adamantiades, Kenton, & Braun 1984). It is thus indicative of energy used in enrichment when feed and product quantities are expressed in kilograms. As implied above, there is a trade-off between the amount of natural uranium feed and the number of SWUs required to produce enriched uranium. How uranium is enriched depends on the amount of uranium feed (UF_6) at the beginning of the process; the amount of SWU used and the concentration of U-235 atoms left over (tails assay) at the end of the process. The level of product enrichment is set by the type of nuclear power reactor specifications Thus, by varying the level of tails assay, the enrichment plant can find the most economical combination of UF_6 feed and SWU required for enrichment. Reducing the tails assay (in terms of % enrichment) results in a reduction of natural uranium feed, but also increases the SWU requirements. As a result, the optimum balance between SWU and the quantity of natural uranium feed will depend on the price of uranium in comparison to the price of enrichment. When uranium prices are low, enrichment plants will most likely operate with higher tails assay percentages (i.e. they will “waste” uranium but save energy by using less SWUs).

4.2.5.4 Fuel fabrication

The final stage in the “Front End” of the nuclear fuel cycle entails the transformation of the enriched UF_6 to uranium dioxide (UO_2) and the fabrication of the fuel for use in the reactor of the nuclear power station. Enriched, solid UF_6 arrives from the enrichment plant at the fuel fabrication facility, where it is heated into a gaseous state. Ammonia, gaseous oxygen, and gaseous hydrogen are then added to yield uranium dioxide powder. The UO_2 powder is finally compressed into cylindrical pellets which are sintered to a structure resembling ceramics and are ground to final dimension, after which between 300 and 370 of them are placed in zirconium alloy (zircaloy) tubes. The tubes are pressurized with helium and sealed to form fuel rods, which are then bundled into fuel assemblies and placed in the nuclear reactor (Vattenfall AB 2004a).

4.2.6 Nuclear power plant operation

The description of the reactor and its operation has already been provided in Section 4.2.2.

In order for the reactor to become operational, the fuel rods are positioned in the reactor core while the nuclear reaction is controlled by using the control rods. After a predefined period of time a certain percentage of the fuel rods are replaced, while existing fuel rods are moved to new positions within the core. This allows for more efficient burning of the fuel, thus maximising reactor output. This process of refueling the reactor leads to reactor downtime while the rods are being replaced but also while the reactor is being started up again after the shutdown. However, the amount of downtime is not only heavily dependent on the reactor type but also on the scale of the refueling taking place. In this work it has been assumed that in each refuel one third of the reactor is replaced. The removed fuel rods classified now as “Spent Fuel”, are placed in a protective environment where they are cooled and monitored until such time as they are taken for interim storage and/or reprocessing.

4.2.7 “Back End”

The final stages of the nuclear fuel cycle, otherwise know as the “Back End”, cover the processes relating to the disposal of the nuclear spent fuel, low and intermediate wastes arising from the nuclear power plant’s operation as well as the storage of high level wastes and materials created from the decommissioning of the power plant at the end of its operational lifetime.

4.2.7.1 Decommissioning

At the end of the life of any power plant, it needs to be decommissioned, decontaminated and demolished so that the site is made available for other uses. For nuclear plants, the term decommissioning includes all clean-up of radioactivity and the progressive dismantling of the plant.

The International Atomic Energy Agency (as quoted in (WNA 2007)) has defined three options for decommissioning:

- Immediate Dismantling (or Early Site Release/Decon in the US: This option allows for the facility to be removed from regulatory control relatively soon after shutdown or termination of regulated activities. Usually, the final dismantling or decontamination activities begin within a few months or years, depending on the facility. Following removal from regulatory control, the site is then available for reuse.
- Safe Enclosure (or Safestor): This option postpones the final removal of controls for a longer period, usually in the order of 40 to 60 years. The facility is placed into a safe storage configuration until the eventual dismantling and decontamination activities occur.
- Entombment: This option entails placing the facility into a condition that will allow the remaining onsite radioactive material to remain on-site without the

> requirement of ever totally removing it. This option usually involves reducing the size of the area where the radioactive material is located and then encasing the facility in a long-lived structure such as concrete, that will last for a period of time to ensure the remaining radioactivity is no longer of concern.

Currently, experience in decommissioning is fairly limited. Worldwide, as of 2005, the IAEA reported that eight power plants had been completely decommissioned. A further 17 had been partly dismantled and safely enclosed, 31 were being dismantled prior to eventual site release and 30 were undergoing minimum dismantling prior to long-term enclosure (WNA 2007). In Europe, several countries are actively engaged in various stages of decommissioning their nuclear facilities. However, there is little consensus with respect to the best method for decommissioning, with most countries either opting for a delay before final dismantling begins (usually 25-50 years) or else examining each facility on a case-by-case basis.

The U.K.’s experience with decommissioning is based mainly on the operations undertaken at the country’s Advanced Gas Reactor (Windscale) and Magnox reactors (Berkeley, Trawsfynydd and Hunterston). The United Kingdom Atomic Energy Authority (UKAEA) is also undertaking decommissioning work at their sites at Winfrith, Harwell, Windscale and Dounreay, all of which represent specialised facilities (a Steam Generating Heavy Water Reactor, a Liquid Effluent Treatment Plant, a Advanced Gas Reactor as previously mentioned and a Fast breeder reactor). At Dounreay, UKAEA's largest site, operations have now ceased and a 50 year programme has commenced to decommission all the site plants, including pilot power plants (UKAEA 2007). Other examples of decommissioning occur at the BNFL site at Sellafield, and include a Separation Plant, Plutonium recovery plant, and a Caesium extraction plant among others. Most of the decommissioning of reactors follow the strategy of “Safestor”, the safe enclosure being reached either promptly after shut-down (e.g. in Trawsfynnyd) or after a deferment of about 35 years (like Berkeley and Hunterston). The main incentive to select the "Safestor” and "deferred dismantling" strategy for the gas-cooled reactors is based on the reduction of dose rate with time of the main radiating isotopes, which decrease naturally up to a factor 10,000 after about 100 years (Co-ordination Network on Decommissioning of Nuclear Installations 2008).

Decommissioning sequence based on the “Safestor” approach

For the purposes of this study, it has been assumed that the “Safestor” option is chosen, as the preferred decommissioning procedure in the U.K. . This decision is based on the National Decommissioning Authority’s (NDA) apparent preference for this method as stated in their 2006 Strategy outline document. In that report, they also state that they are trying to build a business case for the decommissioning of facilities in 25 rather than the current 125 year timeframe (NDA 2006). As such, it could also be argued that that scenario would fall closer to Options 1 than 2 as outlined by the IAEA. However, as the main differences between these options appear to be the timeframe, rather than any fundamental procedural variance, it is felt that the approach modelled in this study covers both.

The following sequence of events during decommissioning is taken from (Storm van Leeuwen 2007), and is loosely based on plans proposed by the NDA (NDA 2006):

Stage 1: Nuclear fuel removal

After the reactor ceases to operate, the spent fuel is removed from the power station and placed in some form of interim storage. The reactor and supporting systems are then also disconnected and various forms of dismantling take place, to prepare the facility for the next stage of decommissioning. The first stage is usually expected to take less than 5 years to complete.

Stage 2: Decommissioning

During this stage, various parts of the reactor and surrounding structure that have become irradiated during the power plant's lifetime are chemically and mechanically cleansed. At this point, separation of materials is also undertaken, with Low Level Waste (LLW) being sent to a repository and Intermediate Level Waste (ILW), placed in interim storage, probably on site. Any ancillary buildings that are no longer needed and that do not pose a contamination threat are then demolished. This stage can take up to 20 years to complete following which the reactor itself, as well as any other radioactive equipment are then sealed off and allow to "cool down".

Stage 3: Care and Maintenance

At this point, the sealed off equipment at the power plant is kept under surveillance to ensure that it remains in a safe condition. There is no agreement as to exactly how long this stage should last, but a minimum period of 30 years is seen as necessary, while the NDA expects between 80-100 years. A point of note is the fact that only a few plants worldwide have reached this stage.

Stage 4: Reactor dismantling and final site clearance

In this final stage, the radioactive parts of the reactor are dismantled, cut up into smaller parts where necessary, and packaged for final disposal. Most of this phase will have to be carried out using remotely controlled equipment due to the health hazard represented by the high levels of radioactivity. The packaged waste is then transported to a geological depository and sealed off. (Storm van Leeuwen 2007) suggests that this stage could be completed in 5-10 years

Modelling of the Decommissioning Phase

Despite the above examples of decommissioning in E.U. countries, almost no empirical data is available on this phase of the life cycle. What little does exists, is based on estimates of the projected economic costs and therefore existing studies that cover the decommissioning phase employ the I/O method, in order to establish energy requirements and the associated emissions. (Storm van Leeuwen 2007) provides a summary of existing studies, but highlights that it is not possible to establish whether some of the studies are using the same reference case as their basis.

4.2.7.2 Waste from the nuclear fuel cycle

Waste is produced in almost all stages of the nuclear cycle. It is important to note that nuclear wastes are not, for the most part, toxic chemicals, but isotopes of "everyday" molecules that emit various forms of radiaton (alpha, beta and gamma) as the return to an inactive form. The radioactivity of all nuclear waste decays with time. Each radionuclide contained in the waste has a half-life, which is the time taken for half of its atoms to decay and thus for it to lose half of its radioactivity. Radionuclides with long half-lives tend to be alpha and beta emitters - making their handling easier, while those with short half lives tend to emit the more penetrating gamma rays. Eventually all radioactive wastes decay into non-radioactive elements. The more radioactive an isotope is, the faster it decays (Uranium Information Center & WNA 2006).

Radioactive wastes can be classified into the following categories:

Spent Fuel (SF): When the uranium fuel in the reactor has been used up, it is removed and stored in ponds where the water provides both shielding and cooling. Currently, spent nuclear fuel from the UK's Magnox and AGR nuclear power stations is transported to Sellafield for reprocessing. Spent nuclear fuel from Sizewell B PWR power station is not reprocessed and is stored in storage ponds (Sustainable Development Commission 2006d).

High level waste (HLW): Because of its radioactivity, HLW generates heat, which has to be taken into account when designing storage and disposal facilities. HLW arises in the UK initially as a highly radioactive liquid, which is a by-product from the reprocessing of spent nuclear fuel. By 2015, the majority of HLW will have been transformed into a 'passively safe' solid form by a treatment process called 'vitrification', which involves adding the HLW to molten glass and pouring the mixture into 150 litre capacity stainless steel containers. Current plans are that vitrified HLW be stored for at least 50 years, to allow a significant proportion of the radioactivity to decay away, for the waste to become cooler, and so make it easier to transport and dispose of.(CoRWM 2006)

Intermediate level waste (ILW): ILW is waste with radioactivity levels exceeding the upper boundaries for LLW (see below) but which does not generate enough heat for this to be classed as HLW (i.e. heat does not need to be taken into account in the design of storage or disposal facilities). ILW arises mainly from the reprocessing of spent fuel and from general operations and maintenance at nuclear sites, and can include metal items such as fuel cladding and reactor components, graphite from reactor cores, and sludges from the treatment of radioactive liquid effluents. As such, many wastes from the decommissioning of a power station would be included in this category. Typically, ILW in the U.K. is packaged for disposal by mixing it with cement in highly-engineered 500 litre stainless steel drums (or for large items in higher capacity steel or concrete boxes) (CoRWM 2006).

Low level waste (LLW): LLW is the lowest activity category of radioactive waste. The LLW that is currently being generated consists largely of paper, plastics and scrap metal items that have been used in hospitals, research establishments and the nuclear industry. In future there will also be large volumes of LLW in the form of soil, concrete and steel, as existing nuclear facilities are decommissioned. Although LLW will make up more than 90 per cent of the UK's waste legacy by volume, it will contain less than 0.0003 per cent of the total radioactivity. Most operational LLW is super-compacted and sent for disposal in the LLW repository (LLWR) near the village of Drigg in Cumbria, where it is mixed with cement and packaged in large steel containers. These are then placed in an engineered vault a few metres below the surface (CoRWM 2006).

The issue of the storage and disposal of nuclear wastes is still largely unresolved. After many, mosly unsuccessful consultations, the Government created the Committee on Radioactive Waste Management (CoRWM) in 2003, which was tasked with making recommendations for the long-term management of the UK's higher activity wastes that “would both protect the public and the environment, and inspire public confidence”(CoRWM 2006). The committee was given a “blank sheet” and asked to investigate all options relating to the disposal/management of radioactive waste, in many ways covering the same ground as previous consultations had. One of the first tasks that CoRWM undertook was to create an inventory of the U.K.’s stock of radioactive waste. In July 2005, it published a report detailing current inventories as well as waste expected to be created by existing plant by the end of their operational lifetime (CoRWM 2005). It also included values for the waste expected to arise from a programme of new nuclear build, based on the AP1000 reactor.

In 2006, CoRWM published their final recommendations to the Government. These included the adoption of geological disposal (i.e. the burial of radioactive waste 200 – 1000m underground, in a purpose built facility with no intention to retrieve the waste once the facility is closed) as the best available approach for the long-term management of all radioactive waste identified in the earlier inventory. The Committee urged for progress to this stage to be made as soon as possible, while “maintaining public and stakeholder confidence”. The other main point made by the CoRWM was the need for “a robust programme of interim storage [to] play an integral part in the long-term management strategy” (CoRWM 2006).

4.2.7.3 Interim Storage for radioactive waste

Interim storage is the “status quo” in the UK and it is the first stage of a long-term management strategy. There are several types of interim stores in use. These range from historical facilities built in the early days of the U.K.’s nuclear programme (the waste in which is soon to be emptied, treated and package and decommissioned), to more recent facilities, built in the last decade for packaged wastes. In principle, there is a difference in the more recent design of stores that anticipate that a disposal option will be implemented in some tens of years, and historical stores (which were for untreated waste) whose lifetime represented the longest that technology could then achieve. The design life for these newer facilities is of the order 50 years, although it may be possible to extend their lifetime to 100 years given appropriate maintenance (Sustainable Development Commission 2006d). Currently, U.K. HLW is stored and cooled at BNFL’s facility in Sellafield and UKAEA’s facilities at Dounreay. Intermediate Level Waste is kept at several sites around the country and usually close to nuclear power stations, while LLW waste is disposed of at the site at Drigg. There is also a small amount of LLW that cannot be disposed of due to volume or chemical composition, which is kept at the Sellafield site (Select Committee on Science and Technology 1998).

Spent Fuel

The UK approach to the interim storage of spent fuel is primarily based on wet storage within dedicated storage ponds at BNFL's Sellafield site. Approximately 50,000 tonnes of LWR, Magnox and AGR spent fuel in some 30,000 flask transports have been delivered to Sellafield for interim storage prior to reprocessing. In addition, there is an at-reactor dry store in operation at Wylfa Nuclear Power Plant. This currently has the capability to store up to 280 tHM in a three CO_2 cooled dry storage cells used for short-cooled Magnox, with a further two air cooled dry storage cells capable of storing up to 700 tHM of Magnox spent fuel. Following interim storage the fuel from Wylfa is transported to Sellafield for reprocessing. The approach taken at Sellafield has wherever possible been to store spent fuel in sealed containers thus protecting the ponds from excessive contamination. For LWR fuels this has been within Multi-Element Bottles (MEBs), whereas Magnox and AGR fuels are stored in skips.

There are two generic types of LWR flask within BNFL's fleet which are distinguished by the bulk shielding requirement: (a) a thin walled rolled steel body with internal lead shielded liner and (b) a thick wall forged steel body without liner. The spent fuel is carried within Multi-Element Bottles (MEBs) or within an open basket. The flask cavity and MEB are filled with water during transport (IAEA 2007).

The most recent reactor in the UK, the Sizewell B Pressurised Water Reactor (PWR) was commissioned in 1995 and uses low enriched fuel in zirconium alloy cans. The power station was designed with enough storage capacity so that its lifetime fuel could be stored on site. This is expected to amount to some 1000 tHM and is currently the responsibility of British Energy (BE) (NDA, Environmental Resources Management Limited (ERM), & Integrated Decision Management Limited (IDM) 2007).

4.2.7.4 Intermediate Level Waste (ILW)

Intermediate level waste is radioactive material which falls between low level waste (LLW) and high level waste (HLW). It is sufficiently radioactive to require shielding and containment and special arrangements for its handling. ILW consists mainly of metals, with smaller quantities of organic materials, inorganic sludges, cement, graphite, glass and ceramics. ILW mainly arises from the dismantling and reprocessing of spent fuel and is defined by the amount of radioactivity it contains per unit weight.

Government policy prior to 1995, was that ILW should remain untreated for as long as it was safe to do so (so as not to foreclose any disposal options). This has meant that only a small proportion (20%) of existing ILW had been conditioned. Most of the remainder, which has arisen from nuclear industry operations over many decades, was stored in untreated form on nuclear sites. Such storage conditions of some ILW led to the Nuclear Installations Inspectorate (NII) increasing the emphasis on the need for potentially mobile wastes to be conditioned.

At present there is no facility in the UK for the long-term management of ILW. Specially designed interim surface or sub-surface storage waste facilities are currently used to ensure the safe storage of radioactive waste pending the availability of a long-term management/disposal option. Most ILW is stored at the site where it is produced. ILW is stored in water filled concrete tanks, or in a variety of steel containers or immobilised in standard packages and kept within dry, above-ground concrete stores.
For most ILW currently arising, packaging consists of conditioning in cement based materials within 500 litre stainless steel drums. Larger items are conditioned in higher capacity stainless steel or concrete boxes. There are a number of ILW plants operating at Sellafield, Dounreay, Windscale and Trawsfynydd. Limited facilities for storing ILW from hospitals and industrial, educational and research establishments are also in operation (DEFRA 2006).

Around 65 per cent of ILW is currently held at Sellafield. Much of this is still in raw form but a number of plants are operating, or are planned, to condition this waste. The main conditioning plants, with the dates at which they did or will start operating, and the wastes which they deal with, are:

- the Magnox Encapsulation Plant (1990, for Magnox cladding);
- the Waste Encapsulation Plant (1994, for THORP wastes and retrieved solids/sludges);
- the Waste Packaging and Encapsulation Plant (1994, for flocs and sludges);
- the Waste Treatment Plant (1996 for plutonium contaminated material) and
- the Drypac plant (2003, for swarf, sludge and miscellaneous beta/gamma waste).

At the site, there are several stores in use and planned to hold the conditioned waste, all of which meet modern safety standards. The stores have design lives of the order of 50 years and BNFL estimate that they could continue to be used safely for 80-100 years. The remaining ILW is held at various nuclear sites. Much of it is held at nine licensed Magnox power stations, at Dounreay and Harwell, and at Aldermaston. At the Magnox and advanced gas-cooled reactor (AGR) power stations, the preferred strategy is not to build new stores for conditioned wastes. Instead the aim is to place such wastes in the 'safestores' which BNFL (at the former Magnox Electric sites) and British Energy (Nuclear Electric and Scottish Nuclear) plan to build around the reactor and other major buildings when they are decommissioned and would also hold wastes arising from clearance of peripheral plant and buildings. The safestores would remain in place for about 130 years, to allow radioactive decay, then all wastes would be removed and disposed of, and the buildings demolished (Select Committee on Science and Technology 1998).

4.2.7.5 Low Level Waste (LLW)

The UK’s Low Level Waste Repository (LLWR) at Drigg, in Cumbria, has been operating since 1959. Although it was originally constructed for the disposal of waste from Sellafield, it receives LLW generated on other nuclear sites throughout the UK and wastes from the non-nuclear sector, excluding hospitals and universities. Since 1988 it has been concrete lined and LLW for disposal has to be packed in special containers. The remainder is stored on site pending a final disposal solution.(British Energy 2002). The NDA, at the time of writing was looking into providing additional disposal capacity to meet short to medium-term strategic requirements (i.e. delivery of a new disposal vault).

The future capacity of the LLW Repository is dependent on the approval for construction of a number of additional disposal vaults at the site. In 2007, there were seven historic disposal trenches and one concrete vault. The plans originally devised by BNFL were based around the construction of seven further vaults to provide 700,000 m^3 of LLW disposal capacity until 2050. However, estimates suggest that there would still be insufficient capacity at the LLW Repository for the anticipated arisings of LLW generated by decommissioning and clean-up. It is expected that the current disposal vault at the LLW Repository will be filled by 2008. Contingency arrangements are, therefore, in hand for the site to continue to offer a disposal route for LLW from nuclear and non-nuclear industry waste generators until the construction of the next disposal vault (Vault 9).(NDA 2006)

4.2.7.6 Final Storage for radioactive waste

A significant aspect of the nuclear fuel cycle is the final deposition of the nuclear wastes created by the fuel cycle. Currently, several countries are in the process of evaluating the various options for final disposal. At the time of writing, no country has yet decided what form this final disposal should take. However, one of the most promising options seems to be that of a deep underground repository placed in stable geological formations. Several countries seem to be opting for this solution, with the U.S.A (considering the site of Yucca Mountain in the Nevada desert), Belgium, Germany, the U.K. and Sweden all investigating the feasibility of this option. The Swedish company Vattenfall is considering the option of creating such a facility near their Oskarshamn Power Station, which also houses the company's Central Interim Storage Facility (CLAB) (Vattenfall AB 2004a). Finland, on the other hand, is leading the way after voting in 2001 to create a deep underground repository in the southwest of the country, to accept existing wastes and those set to arise from the operation of the new Okiluoto NPP (Cameco 2006b). The U.K. has also been evaluating the possibility of an underground repository, with both NIREX and the Committee on Radioactive Waste Management (CoRWM) considering the feasibility of such a scheme (CoRWM 2006).

4.2.7.7 Reference HLW/SF Concept

NIREX'S remit originally included only ILW and LLW and hence it's work was focused on the development of a repository concept for those waste streams. This remit was later broadened however, to include HLW and SF. With encouragement from U.K. Government, NIREX conducted joint work with other national organisations (SKB (Sweden), Nagra (Switzerland) and NUMO (Japan)) to examine the extent to which the vast amount of work undertaken internationally on the long-term management of high-level waste (HLW) and spent nuclear fuel (SF) can be applied in the UK (NIREX UK LTD 2005e). The result of the collaboration has led to the framework for the HLW/SF Concept. The Reference HLW/SF Concept is a generic concept that could potentially be applied to a variety of sites in the U.K. and incorporates many of the stages described in the PGRC above. The Reference HLW/SF Concept is based on the KBS-3 Concept developed by the Swedish agency SKB, resulting from the collaboration between Swedish and Finnish national programmes. The concept is centred around the encapsulation of the waste in copper canisters which are then surrounded by bentonite clay and then deposited in vertical holes drilled along access tunnels at a depth of 650m. The holes would then be backfilled with a mixture of crushed rock (70%) and bentonite (30%) (NIREX UK LTD 2005b). NIREX itself, has clearly stated that the work on the HLW/SF Repository is not as advanced as that for the ILW/LLW Phased Geological Repository Concept (described in following sections) (NIREX UK LTD 2005e), and therefore the modelling of this phase could be subject to significant change.

4.2.7.8 Phased Geological Repository Concept for ILW/LLW (PGRC)

The Phased Geological Repository Concept (PGRC) was developed by NIREX to provide safe, long-term management for ILW and for LLW that is not suitable for disposal in existing near-surface facilities (NIREX UK LTD 2005a). The PGRC is a multi-barrier system comprising physical, chemical and geological barriers to ensure any radioactivity that returns to the human environment in the future is within acceptable levels. A key feature of the concept is that of retrievability, focusing on a phased and reversible approach, which is based on storing waste deep underground, where it is less vulnerable to disruption by man-made or natural events. The concept is designed to prevent, or at worst slow down to a safe level, the release of radio-toxic substances to the environment whilst the natural process of radioactive decay occurs. The incorporation of monitoring and retrievability means that choices on how, and if to proceed towards closure of the facility are offered to future generations, in accordance with the general concept of intergenerational equity.

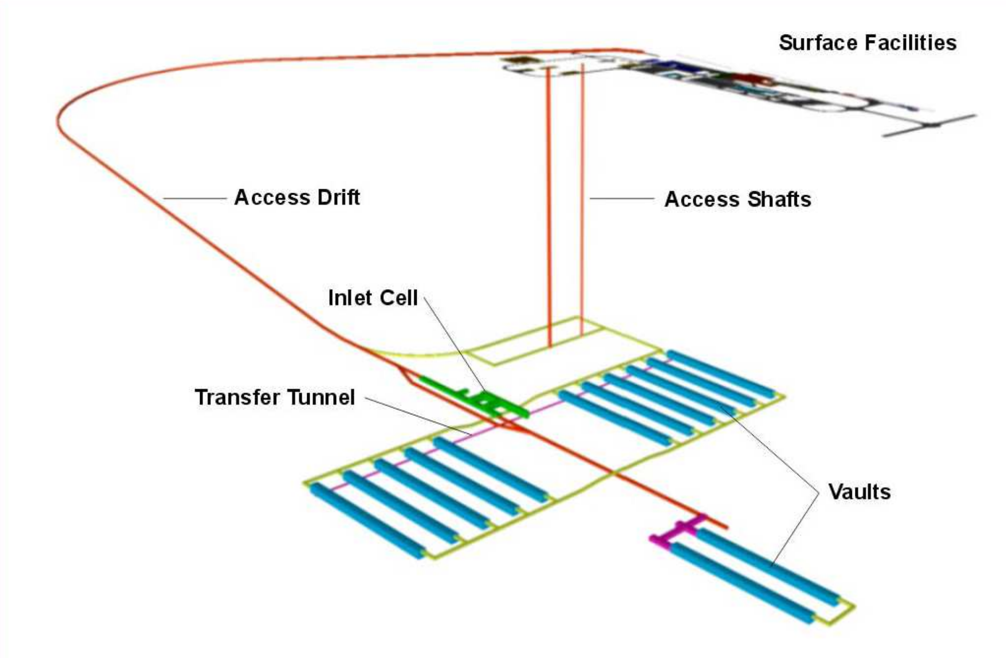


Figure 4.2 Generic Repository Concept

The PGRC covers the final disposal of ILW and LLW that is otherwise unsuitable for disposal at the facility at Drigg. Once waste has been packaged appropriately to NIREX standards and specifications, it is transported to the centralised repository facility were it is emplaced in the purpose-built vaults at a depth in suitable geological formations. This would be followed by a period of monitoring which could, in theory, be extended indefinitely, providing the possibility of retrieving the waste should that be required. Otherwise this stage is followed by the backfilling of access tunnels to the waste and the permanent enclosure of the material.

4.3 Wind Power system

Although the processes relating to wind power systems are not generally considered as complex as those relating to the nuclear fuel cycle, nonetheless they present their own challenges. As the most important input to the system is the fuel, wind which by its nature cannot be controlled, it is of vital importance that all preliminary research is carried out with as much detail as possible. This section presents some of the most important governing concepts used in wind farm design and provides an introduction to the principles of calculating the energy yield of a wind farm.

4.3.1 The nature of wind

Global wind patterns are created from the uneven heating of the Earth's atmosphere by the Sun and from the spinning of the planet around its axis. The earth's atmosphere is constantly subjected to an exchanging of energy with outer space and thus can be thought of as a mixture of gases forming a system, upon which work is done. The sun provides energy to the atmosphere and results in a difference in the relative heating of the earth's surface. This difference, in turn, creates regions where the air pressure is temporarily higher or lower than that of neighbouring regions, resulting in a movement of atmospheric gases from regions of high pressure to those of lower pressure. As such it can be said that the driving mechanism of air movement is the difference in air pressure between different regions on the earth. Within the atmosphere, these regions combine with other effects such as solar radiation, humidity and cooling to name but a few, to create complex mechanisms that affect global wind patterns.

Near the equator, where relative levels of insolation (a measure of solar energy received on a given surface area) are higher, warm air rises and colder ground air moves in to replace it. The warm air then circulates in the atmosphere and sinks back to the surface in colder regions. This large scale movement of air masses is strongly influenced by Coriolis forces which are generated by the Earth's rotation, and results in a global pattern of wind circulation. This results in the creation of distinct zones of air movement around the planet. Two such zones are the large belts of wind patterns created between the equator and the 30^o north/south latitudes, where winds move from east to west and are known as the "trade winds". Further from the equator, between the latitudes 30^o and 60^o north/south, the winds blow predominately in the opposite direction (i.e. west to east) as a result of the "trade winds" completing a circular pattern. A diagram showing these wind patterns can be seen in Figure 4.3 taken from (NASA 2007). The non-uniformity of the Earth's surface also causes variations in this global pattern of wind movement. The effect of the interaction of these smaller scale circulation variations with the global variations, create complex interactions that make the forecast of weather (and subsequently the forecasting of wind patterns) difficult. Local variations are also influenced by topographical parameters (hills, mountains, bodies of water etc) and thermal effects (the relative heating/cooling effects of different areas of the Earth's surface).

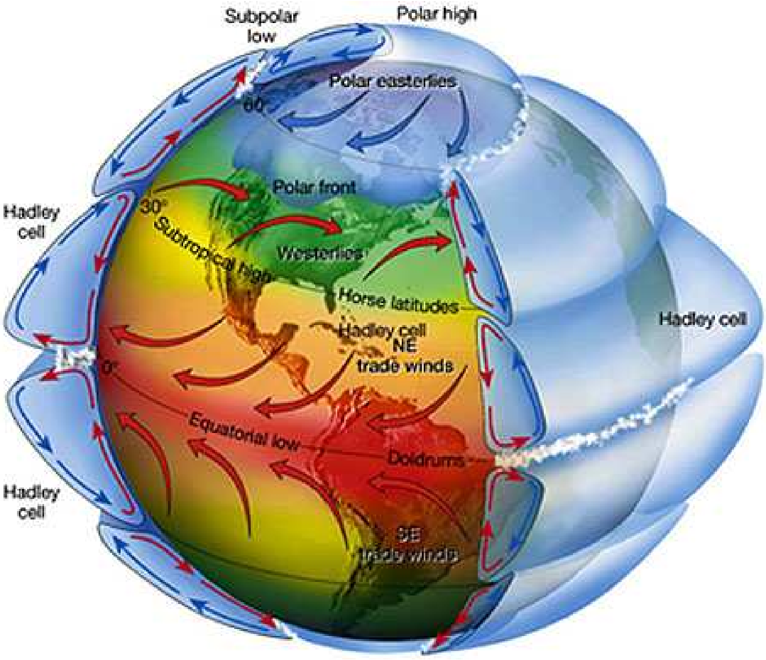


Figure 4.3 Global wind patterns

In many ways, the most important factor affecting the wind resource is its variability. Apart from the large scale global and more local topographical deviations mentioned previously, temporal variations also play an important role. The resource may vary from year to year and also demonstrates longer term variations over a period of decades. This uncertainty can affect the longer term predictions for wind farm energy yields and influence hence their economic viability. On a shorter timescale, seasonal variations within a year are also normal. These however, tend to be more predictable and better understood and are influenced by the different weather systems that may affect the region (i.e. high/low pressure regions). Differences also occur on a diurnal basis (i.e. between day and night time) and are again predictable with a high level of certainty. On even shorter time scales of hours and minutes, wind pattern variations are much harder to predict and can have significant effects on the performance of wind farms, and are ultimately responsible for phenomena such as variability. These variations on the time scale of hours and minutes are caused by turbulence. Turbulence is a complex fluctuation of wind flows in short time frames (as described previously) and can generally be attributed to two causes; air friction with Earth's surface due to topographical features and thermal effects that cause airflows to move in a vertical direction and hence interrupt the more horizontal flow of wind. Turbulence is a climatic effect that adds further uncertainty to the prediction of wind regimes.

Overall, however, it can be stated that wind patterns at given locations follow repetitive trends. While year to year annual wind speed variations remain hard to predict because wind is driven by the sun and the resulting seasonal variations, wind patterns tend to repeat over the period of a year (Patel 1999). As such, they can be readily described in terms of probability distribution. For many sites, and especially in northern Europe, the variations of wind speeds during a year are best described by the Weibull distribution. This distribution can be described with two parameters, 'k' the shape parameter that varies from 1 to 3 and is related to the mean wind speed at the site and 'c' the scale parameter that depends on the aforementioned k-factor (Johnson

2001). The probability of the wind speed being a value *v* during any time interval is given by:

$$h(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} e^{-\left(\frac{v}{c}\right)^{k}} \quad \text{for } 0 < v < \infty \qquad (4.1)$$

The wind patterns, thus described, can then be used to provide an estimate of the energy that may be available for extraction from a given site.

4.3.2 Wind turbine history and development

Wind energy has been used by humans for thousands of years to propel sailing ships or later on, on land to convert wind into mechanical energy to pump water and grind grain. Descriptions of the use of wind turbines stretch as far back as antiquity with wind turbiness being used both in China and the near East.

Windmills appeared as early as 1194 in England and wind powered structures specifically for corn grinding from 1439 in Holland (Johnson 2001). By the 16th and 17th centuries, wind mills were common across Europe and were used for water pumping, grinding of millet, corn and other farming produce while also providing the necessary power for the nascent textile industries of the time Wind mills were also imported in to the U.S.A from the mid 1700s and helped pave the way for the settlement of western regions, since they provided power for basic household needs such as well pumping.

From the late 19th century onwards, research into the use of wind turbines specifically to generate electricity was undertaken in various locations, including Denmark and Scotland. By 1910 hundreds of wind turbine units were in operation in Denmark (Johnson 2001). In 1888 the first 12 kW DC wind turbine was constructed by Charles F Brush in the U.S.A. At the time however, there was little interest in using wind energy apart from battery charging at remote dwellings until the 1250 kW Smith-Putnam wind turbine was constructed on Grandpa's Knob, Vermont U.S.A. in 1941 and remained the largest wind turbine for about 40 years ((Shathyajith 2006). At the same time in Europe, many innovative wind turbine generators were being designed and built. The 100 kW, 30 m diameter Balaclava wind turbine was constructed in 1931 on the shore of the Caspian sea while the Enfield Andreau 100 kW 24m diameter pneumatic design, based on drawing in air into the tower power power pumps, was constructed in the U.K in the early 1950s. In Germany, Prof. Hutter developed a series of advanced horizontal axis designs of intermediate size that used airfoil type fibreglass blades with variable pitch capabilities to provide light weight and high efficiencies in the 1950s and 1960s (Johnson 2001). In general however, interest in wind power waned until the 1970s when the Middle East oil embargoes renewed the interest in alternative energy sources. Since then, work carried out in the U.S.A. by NASA and the Department of Energy, as well as work in Denmark and Europe in general, has paved the way for the development of wind energy into a mainstream energy solution

Generally, a wind turbine can be defined as a machine that captures the kinetic energy in the wind through the exertion it applies to its blades and converts it to rotational energy which is then used to generate electricity. In order to intercept the higher wind speeds available at higher altitudes, wind turbines are placed on towers while grouping many machines together allows for a higher extraction of energy from a given area.

There are two different types of turbines: vertical axis and horizontal axis. Vertical axis wind turbines (VAWT) are so called because their main rotor shaft runs vertically. Various versions of this type of turbine design have been created, the two main types of which are the Darrieus design which has curved vertical blades and uses the lift they create to rotate; and the Savonius rotor which resembles a cup anemometer in its method of operation since it uses drag to rotate. A third popular design is the Giromill, which is, in effect, a variation on the Darrieus design. The main advantages of the VAWT design is that it allows for all the heavy equipment such as gearboxes and generators to be placed at ground level thus allowing for easy access; it also does not need to align itself with the wind direction thus ensuring that there are no losses as it realigns itself to a new direction. Despite these advantages, VAWT have not been a commercial success mainly due to the difficulty in erecting them and the fact that they can suffer from the high turbulence that exists near ground level. Conversely, the wind speeds available to a VAWT are also not as high as those further up, limiting its output. As a result VAWT tend to have lower coefficients of performace (i.e. are less efficient at extracting energy from the wind; see next section) than their horizontal axis counterparts.

The most common wind turbine design currently in use worldwide is the Horizontal Axis Wind Turbine (HAWT). In this design the rotor axis, generator and drivetrain are placed inside the nacelle at the top of the tower. The main advantage of this design is the higher coefficient of performance (compared to the VAWT) and the fact that by being placed on a tower, the turbine can intercept the higher wind speeds available at height. Also because of the tower, HAWT can be used on sites with high shear, since they are not as affected by the wind speed differentials across their (shorter) blades as are VAWTs The main disadvantages of this design include the difficulty and expense of installation of the towers and the fact that there are losses associated with the response time between a change in wind direction and the realignment of the wind turbine blades.

In order to extract the most energy from the given wind resource at any location, developers started early on to groups wind turbines in order to create wind farms. While early wind farms consisted of several machines producing under two megawatts, there is a trend towards larger sites with most recent wind farm developments consisting of large numbers of turbines resulting in capacities of several hundred megawatts. A similar trend can also be seen in the size of individual wind turbines, both in terms of physical size as well as output. Whereas early designs measured rotor diameters of approximately 15 m-50 m and were characterised by outputs of a couple of hundred kilowatts, wind turbine manufacturers have started producing wind turbines of ever-increasing size, culminating in onshore wind turbine sizes of between 1.5 MW to 3 MW, with rotor diameters in excess of 100m. Despite certain individual wind turbine manufacturers continuing to increase the size of their machines, it has been argued that onshore wind turbine sizes are beginning to stabilise in the 1.5 MW to 2MW region (EWEA 2009).

As can be seen from the above most significant developments have, until recently taken place onshore. However since the early 1990s, there was an increased interest in the developing the potential of offshore wind farms, with Denmark installing the first offshore wind farm in 1991. The interest for offshore wind power also grew in the U.K., with the country's first project, North Hoyle, being installed in 2003 and being rapidly followed by Scroby Sands (60 MW) and Kentish Flats (90 MW) in 2004 and 2005, respectively (BVG Associates and Douglas Westwood 2006**)**. Since then, offshore wind has continued to develop strongly, with projects exceeding 1000 MW installed capacity in the development pipeline. Also the average size of offshore wind turbines also exceeds that of their onshore counterparts. Originally, offshore wind turbines were merely onshore models modified to cope with the harsh conditions encountered in an offshore environment. However, wind turbine manufacturers soon realised both the necessity for models designed specifically for the sea environment and the need for larger turbines to make the most of the available wind resource. As a result, most large manufacturers now produce dedicated offshore models, with capacity ratings exceeding 4 MW.

4.3.3 Estimating wind farm energy yield

In order to calculate the potential energy output of the wind farm, it is necessary to estimate the amount of energy that can be captured from the wind. A basic description of the energy in the air can be given using basic thermodynamic equations (Patel 1999). The kinetic energy of a mass of air, 'm', moving with speed V is given by the following equation:

$$E_k = \frac{1}{2} m V^2 \qquad (4.2)$$

The power in the moving air is the flow rate of kinetic energy per second:

$$Power = \frac{1}{2} \dot{m} V^2 = \frac{1}{2} (\rho A V) V^2 \qquad (4.3)$$

which can be rewritten as

$$Power = \frac{1}{2} \rho A V^3 \qquad (4.4)$$

where P = power in the moving air
$\dot{m}$ = mass flow rate
ρ = air density, kg/ m^3
A = swept area of the blades, m^2
V = velocity of the air, m/s

However, the energy that can be extracted from the wind is limited as all the upstream power in the wind cannot be extracted by the wind turbine. Instead some power is left in the wind downstream of the blades, which means that air flow moves with reduced speed.

The actual power extracted by the blades of a wind turbine is the difference between the upstream and downstream powers of the air flow.

$$Power = \frac{1}{2}\dot{m}\left(V_U{}^2 - V_D{}^2\right) \qquad (4.5)$$

Where Power here implies the power extracted from the air

$\dot{m}$ = mass flow rate
V_U = upstream velocity of the air, m/s
V_D = downstream velocity of the air, m/s

As before, the mass flow rate of air through the blades is determined by the average wind speed passing through the blades:

$$\dot{m} = \rho A \frac{\left(\dot{V}_U{}^2 + V_D{}^2\right)}{2} \qquad (4.6)$$

Combining equations (3) and (4) and rearranging the result gives:

$$Power = \frac{1}{2}\rho A V^3 C_p \qquad (4.7)$$

$$where\, C_p = \frac{\left(1 + \frac{V_D}{V_U}\right)\left[1 - \left(\frac{V_D}{V_U}\right)^2\right]}{2} \qquad (4.8)$$

The coefficient C_p expresses the fraction of upstream power that can be captured from the air and is known as the rotor efficiency, power coefficient or, as stated earlier, coefficient of perfomance. It can be proven that C_p can attain a maximum value of 0.59, which is known as the Betz limit (for extensive derivations (Burton et al. 2001)), when the ratio of upstream and downstream wind speeds equals one third. Thus, the Betz limit provides the *theoretical* maximum power that can be extracted from the wind, given the site conditions. In practice however, modern wind turbines achieve lower power coeffients, with values between 0.3 and 0.5 being typical for 3 bladed horizontal wind turbines (Burton, Sharpe, Jenkins, & Bossanyi 2001).

From equation (3) above, it can be seen that the energy in wind is directly related to the cube of the wind speed. Thus an accurate understanding of the wind resource at a given location is fundamental to establishing and exploiting wind power. To do this, knowledge of the site characteristics of the wind farm location is required, as well as the power curve of the wind turbines to be installed at each site. The information relating to the wind regime is of course site specific, and as such, each wind farm has to be modeled on a case-by-case basis. Ideally, average wind speeds measured over a substantial period at specific intervals would be used to estimate the energy available at each site. This type of information, however, is rarely available at initial development stages, so it is usually necessary to create an estimate based on more generic data combined with statistical methods.

The mean power production of a wind turbine, assuming 100% availability, can be calculated by:

$$E = T\int P(V)\,f(V)\,dV \qquad (4.9)$$

where P(V) is the power curve of the wind turbine, f(V) is the probability density function (abbreviated to PDF) of the wind speed and T is the time period (Burton, Sharpe, Jenkins, & Bossanyi 2001).

Wind speeds vary depending on the time of day and the terrain, local weather systems and the height above the ground that they are measured at. For an accurate description of the potential energy yield of site, long term observations directly at the site are required. However, as these are not usually available, other methods can be employed to get an approximate estimate of the wind characteristics of a site. A brief description of the alternatives is given below.

Wind speed Maps and Atlases

Wind speed maps give estimates of the mean wind speed over a location, using data from meteorological stations and other sources. The data is usually represented by contour curves, where the parameters described (i.e wind speed) remain constant along the contour line. Wind Atlases are available for many countries and even whole continents. In the United Kingdom, a wind speed database exists based on the NOABL airflow model. The database contains estimates of the annual mean wind speed throughout the UK which are the result of an air flow model that estimates the effect of topography on wind speed. However, as this is a simplified model, there is no allowance for the effect of local thermally driven winds such as sea breezes or mountain/valley breezes (Burton, Sharpe, Jenkins, & Bossanyi 2001). The model works on a 1km square resolution and makes no allowance for topography on a small scale or local surface roughness (such as tall crops, stone walls, or trees), both of which may have a considerable effect on the wind speed (Foley 2003). The program can provide data for a given grid reference (based on coordinates), as well as for surrounding areas, in 1km boxes at three different heights (10m, 25m and 45m above ground level).

"Measure-Correlate-Predict" (MCP) approach

Given the limitations imposed on the above method of wind speed prediction, the preffered method of estimation of the wind regime at a given location is to use short term wind speed observations from the site combined with more long term data from a nearby weather monitoring station. This method is known as the "Measure-Correlate-Predict" (MCP) approach. In its simplest form, a linear regression can be used to create a relationship between the short term measured wind speeds at the site and the long term data available from the meteorological stations. By calculating the correlation coefficients, it is then possible to use the long term predictions to extrapolate conditions at the site in question for the same time period, which can then in turn be used to predict wind speeds during the lifetime of the project. However, there are also limitations to this method, as it assumed that the wind speed distributions at the site are the same as at the meteorological station, while also the quality of the data at the latter might compromise the accuracy of the predictions (Burton, Sharpe, Jenkins, & Bossanyi 2001). The estimates created by this method also highly site-specific and usually only accurate to the exact position of the onsite mast. As wind farms are usually comprised of many turbines spread out over large areas of land, these estimated values clearly cannot be representative of anything but the simplest sites. To tackle this, a further development in the prediction of wind speeds at a certain location is the use of commercially available computer software that attempt to predict the effects of topography on the wind speed. Using a combination of meteorological data and a description of the site, these programs can then proceed to establish the energy yield of the location. These software packages are usually used in conjunction with the MCP method to better predict the variations in wind regime across large distances. One of the most established software packages for this purpose is WAsP, created by the Risø Institute in Denmark.

4.3.3 Hub height wind speeds

Once the wind regime at a given height has been established through the above methods, it then becomes necessary to estimate the effect of height on the wind speeds. As previously mentioned, wind speeds have the tendency to increase with height, mainly due to the fact that there is less interference from the surface of the air. allowing air flows to approach free stream velocity. Thus wind shear nearer the ground causes lower wind speeds than those observed higher up, resulting in an increase of wind speeds with height.

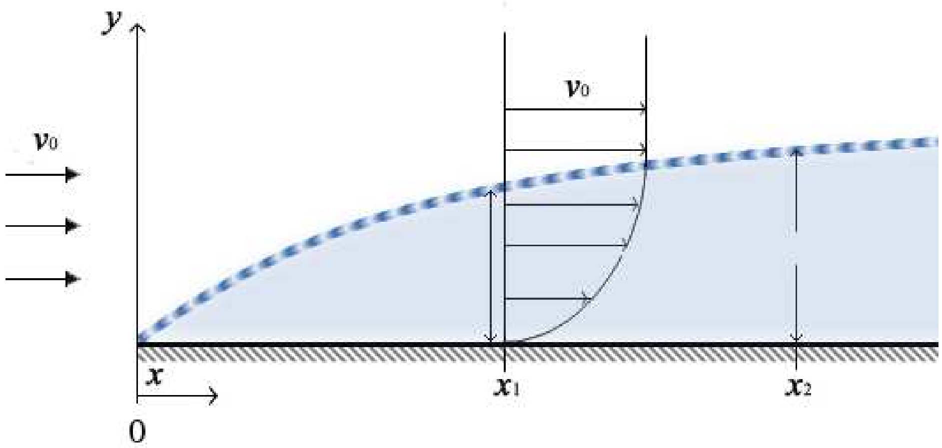


Figure 4.4 Image of boundary layer

It is thus normal, for wind turbines to be mounted on towers which allow them to intercept these faster air flows. Since however measurement masts are rarely of the same height as the tower of the wind turbine, it becomes necessary to find ways to extrapolate the wind speeds calculated at lower heights to the hub height of the turbine. This can be achieved using equations developed from the study of fluid mechanics. Specifically, the variation of windspeed with height can be described using the Prandtl logarithmic law model of wind speed variation with height, where the logarithm of the measurement height is plotted against the recorded wind speed. The Prandtl logarithmic law model is defined below:

$$\overline{U}(z) = \left(\frac{u_*}{k}\right).\ln\left(\frac{z}{z_O}\right) \qquad (4.10)$$

where $\overline{U}(z)$ is the mean wind speed at height z above ground level,

u_* is the friction velocity,

k is the von Karman constant,

z_0 is the roughness length

Using an assumption of neutral atmospheric conditions, the above equation can be simplified to:

$$v = v_{ref} \times \ln\left(\frac{z}{z_o}\right) \Big/ \ln\left(\frac{z_{ref}}{z_o}\right) \qquad (4.11)$$

where v = wind speed at height z above ground level.
v_{ref} = reference speed at height z_{ref}.
z = height above ground level for the desired velocity, v.
z_0 = roughness length in the current wind direction.
z_{ref} = reference height

Many times a more simplified approach to estimating the windspeed will be preferred. This can be accomplished with the use of the Power Law equation. The power law wind shear exponent is defined by:

$$\frac{\overline{U}(z_1)}{\overline{U}(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha} \qquad (4.12)$$

where α is power law wind shear exponent,
$\overline{U}$ is the mean wind speed,
z is the height above ground level

However, the power law wind shear exponent varies with the type of terrain and is also dependent on the height interval over which the equation is applied, making it thus less useful than the logarithmic profile (Burton, Sharpe, Jenkins, & Bossanyi 2001).

As it can be seen from the above expressions, the calculation of wind speeds at given heights is affected by the roughness length, z_o. The roughness length is a parameter that is used as a representation of the roughness of the terrain over which airflow passes. It is defined as the height at which the mean wind speed is zero.

A range of roughness lengths have been defined for typical terrain types and are summarised in Table 4.2, taken from (Danish Wind Industry Association 2008) below:

Roughness Classes and Roughness Length Table		
Roughness Class	*Roughness Length m*	*Landscape Type*
0	0.0002	Water surface
0.5	0.0024	Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc.
1	0.03	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approx. 1250 metres
2	0.1	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approx. 500 metres
2.5	0.2	Agricultural land with many houses, shrubs and plants, or 8 metre tall sheltering hedgerows with a distance of approx. 250 metres
3	0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	Larger cities with tall buildings
4	1.6	Very large cities with tall buildings and skyscrapers

Table 4.2 Roughness classes for different landscapes

4.3.4 Wind Farm Energy losses

The final energy output figures estimated in the previous sections are themselves subject to losses. Losses in general are inherent in the production of energy in all types of power plant, but there are also losses that are highly specific to wind power.

The energy output from each turbine and the wind farm as a whole is subjected to energy losses. These are attributed both to technology specific reasons (wake losses, environmental losses etc.) as well as general losses (maintenance downtime, electrical losses etc.). An analytical summary of the losses assumed for the wind farm model are the following:

Wake effect losses

Wind turbines extract energy from the wind and as the wind progresses downstream from any wind turbine, a wake is created which leads to a reduction in wind speed. As the flow proceeds downstream of a turbine there is a spreading of the wake and the wind speed recovers towards free stream conditions. The wake effect stated here is the aggregated influence on the energy production of the wind farm which results from the changes in wind speed caused by the interaction of the turbines on each other.

Availability losses

Over the lifetime of the project, wind turbines, the “balance of plant” infrastructure, and the electrical grid will not be available the whole time. As such a factor needs to be included to account for the losses incurred when one or all of the above inhibits the production and delivery of electricity. Such losses include, losses due to turbine availability, supporting plant availability and grid availability.

Electrical transmission efficiency

There will be electrical losses experienced between the low voltage terminals of each of the wind turbines and the wind farm Point of Connection, which is usually located within a wind farm switching station.

Turbine performance

In an energy production calculation, a power curve usually supplied by the turbine manufacturer is used within the analysis. However, losses need to be assumed for the discrepancy between power curve measurement conditions and actual site conditions and losses due to high wind shutdown, among others.

Environmental

In certain conditions, dirt and ice can form on the wind turbine blades or over time the surface of the blade may degrade. These influences can impact the energy production of a wind farm. Extremes of weather can also impact the energy production. Finally, tree growth and felling may impact the production of a wind farm in a time varying manner.

Curtailments

Some or all of the turbines within a wind farm may need to be shut down to mitigate issues associated with turbine loading, export to the grid or certain planning conditions. Other restrictions such as noise or visual curtailments can also impact on the final energy production.

5. Nuclear Power lifecycle modelling

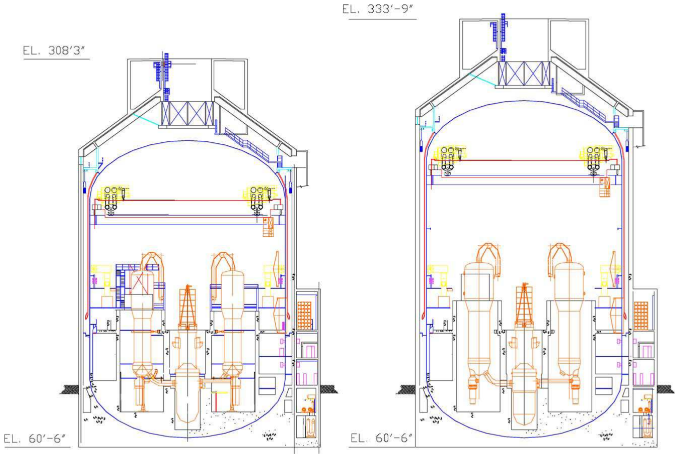
5.1 Introduction

This chapter provides a detailed description of the modelling of the nuclear power lifecycle that was undertaken in this research. After a brief introduction into the nature of nuclear power and the history of involvement in the United Kingdom, an analytical breakdown of the various phases on the nuclear lifecycle is provided. The lifecycle is broken down into three major sections, covering the pre-electricity generation activities (mining and refining the ore, converting it to fuel), known as the “Front End”, the phases directly linked to the nuclear power plant construction and operation, and the activities required once the nuclear fuel has been extracted from the reactor, as well the decommissioning of the reactor, collectively known as the “Back End” of the fuel cycle. In each of these phases, each major modelling input and assumption is explored in detail and issues pertaining specifically to a phase are addressed in the same section (i.e. abundance of uranium is addressed in the section on nuclear fuel supply).

5.2 Nuclear power plant reference case

The Nuclear power plant (NPP) reference case is based on this “next generation” of nuclear reactors, originally aimed for deployment by 2010 (Sustainable Development Commission 2006b). As stated above, the choice was made to use a PWR design as the focus of this study. Specifically, the model was loosely based on the Westinghouse Advanced Passive 1000 (AP1000) Pressurized Water Reactor, as a more complete dataset was available for this design than its main competitor, the AREVA EPR, at the time of writing. However, it is argued that despite certain operational and design idiosyncrasies, the basic characteristics of the chosen reactor are similar to those of the AREVA EPR and therefore common to most Gen. III+ PWR reactors.

The AP1000 is an advanced 1117 -1154 MWe reactor design and is based on the same two-loop configuration as its predecessor, the AP600, while optimising the power output and thus offering a reduction in electricity generation costs through “economies of scale” (Westinghouse Electric Company LLC 2006).



AP600 AP1000

Figure 5.1 Reactor schematic of AP600 and AP1000

The AP600 was 600MWe plant design (seen in Figure 5.1 above from (Schulz 2006)), developed in the 1990s as part of the US Department of Energy Advanced Light Water Reactor (ALWR) Program, receiving final design approval in 1998(Westinghouse Electric Company LLC 2004). Like all PWR designs, the AP1000 is designed to use enriched uranium fuel, but also to operate at a higher fuel burn-up rate, therefore reducing uranium requirements and operational waste. The manufacturer also claims that the AP1000 has been designed to operate on a 100% loading of Mixed Oxide fuel (MOX), should economics and resource availability require this (Westinghouse Electric Company LLC 2006).

The AP1000 uses the same “island footprint” as the AP600, but improves the reactor power output thanks to the extra height of the reactor containment housing (Sustainable Development Commission 2006b). The main characteristic of the AP design is that of the passive safety features. The AP1000 does not require a large network of safety support systems typical of reactors of its kind such as Cooling water systems, AC power and heating, ventilation and air conditioning systems (HVAC). Instead the design utilises only natural forces, such as gravity, convection and gas compression, reducing thereby the risk of failure and the complexity of design. Compared to a traditional PWR design of similar size, the AP1000 uses 50% fewer valves, 80% less piping, 35% fewer pumps and 50% less seismic building volume. Such reductions are also claimed to lead to savings in plant construction and operating costs (British Nuclear Fuel plc & Westinghouse Electric Company LLC 2002). Another major characteristic of the AP1000 design is the modularisation of the design. This permits the different plant components to be manufactured off-site in smaller modules and then transported for final construction to the site. This has a positive impact on the plant construction time and reducing the risks associated with plant financing. It is estimated that plant construction would take approximately 36 months (Schulz 2006).

The N.P.P. model covers all aspects of the nuclear fuel cycle: “Front End” operations (such as mining, milling, conversion, enrichment and fuel fabrication), N.P.P. construction and operation and “Back End” operations such as power plant decommissioning, waste interim storage management and final disposal. It should be noted that the model does not incorporate a “fuel reprocessing” cycle, which is currently typical in the UK A summary of the technical characteristics of nuclear reactor design is given in the table below:

GEN. III+ N.P.P. SUMMARY	
Nominal Output (MW_e)	1,117
Core Thermal Power (MW_{th})	3,400
Fuel Enrichment (%)	4.95
Burn-up (MWd/tU)	48,000
Thermal Efficiency(%)	33%
Refuelling Interval (months)	18
Station Lifetime (years)	60

Table 5.1 Nuclear Power Plant Characteristics

The data is based on a variety of different sources as no single source provided a complete set of figures. The values used in this work are based on the collation of data from (British Nuclear Fuel plc & Westinghouse Electric Company LLC 2002), (Schulz 2006) and (Energetics Incorporated 2005). One of the main assumptions made in this report, is that any new nuclear power station would be built near existing facilities since that would provide automatically an existing infrastructure and more specifically a connection to the national electricity grid. Interest in hosting a new nuclear power station has been expressed by British Energy in their submission to the Government's Energy White Paper (British Energy 2006). Also, given that the required infrastructure (water supply, connection to the National Grid) is already in place at current nuclear power plant sites, it has been assumed in this report that the new nuclear reactor would be built close to the only other existing PWR in the UK, namely at the Sizewell site in Suffolk.

5.3 Nuclear fuel cycle

The nuclear fuel chain used in this report is similar to the supply routes described by several sources connected to the U.K. and international nuclear industry such as (Vattenfall AB Generation Nordic Countries. 2004), (Vattenfall AB 2004b) and in British Energy's "Environmental Product Declaration of Electricity from Torness Nuclear Power Station" (AEA Technology & British Energy 2005). It has been assumed that similar supply routes would be used in this study. The lifecycle modelled in this study is based on 4 mines (one in Canada, two in Australia and one in Namibia) supplying uranium ore to processing facilities in Europe (mostly U.K.-based). The fuel is then used for electricity generation at the N.P.P. and the waste fuel is taken to reprocessing facilities also based in the U.K. and then kept in interim storage. Finally, the treated waste is placed in a final depository. The table below gives an explanation of the different stages and facilities in the nuclear fuel cycle included in this study.

FUEL CYCLE STAGE	PROCESS	FACILITY
Mining	Underground mining	McArthur River, Canada
Milling	Uranium Ore Milling	Key Lake, Canada
Mining and Milling	Open pit Mining &Mill	Ranger, Australia
Mining and Milling	Open pit Mining &Mill	Olympic Dam, Australia
Mining and Milling	Open pit Mining &Mill	Rössing, Namibia
Conversion	U_3O_8 Conversion to UF_6	Port Hope, Canada Springfields, U.K. Malvesi/Pierrelatte, France
Enrichment	Enriched UF_6 production	Capenhurst, U.K. Tricastin, France
Fuel Fabrication	Fuel Rod Fabrication	Springfields, U.K
Electricity Generation	Nuclear Power Station	Sizewell, U.K.
Waste Processing and Interim Storage	Encapsulation and Storage	Generic, U.K.
Final Disposal	LLW/ILW repository HLW/SF repository	No location specified

Table 5.2 Nuclear Fuel Cycle Overview

5.4 “Front End”

Due to the many different stages of the nuclear fuel cycle, it has been necessary in this research to create a flowchart to calculate the material production requirements at each stage of the operation. The flowchart is based on the operational requirements of the reactor throughout its lifetime. These are then translated back into basic ore quantities and the environmental impacts are then calculated based on those quantities. An analytical explanation and breakdown of the flowchart can be found in Appendix B, but a diagrammatical representation of the nuclear “Front End” is depicted below, and illustrates the materials requirements over the lifetime to produce a given output:

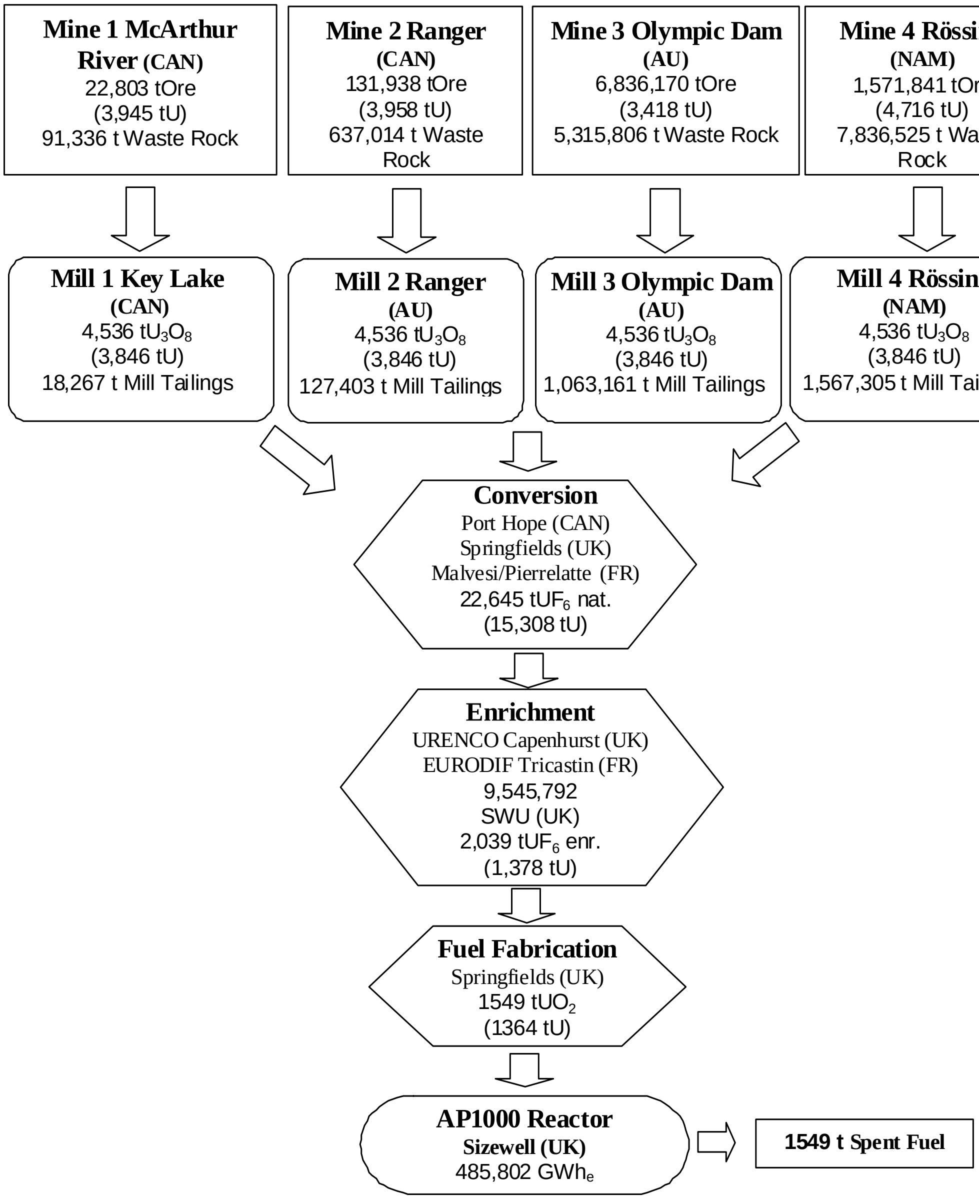


Figure 5.2 Uranium Lifecycle Mass Flow

5.4.1 Mining and milling

The facilities chosen for the models are among the top five producers of uranium in the world as stated in (UIC 2007c). The mines selected here are designated as either underground or open-pit, even though “in-situ” leaching (ISL) mines now make up a significant contribution to the world uranium supplies. In 2006, world uranium supplies were sourced from the following types of mines: underground 41%, open-pit 24%, in-situ leaching 26% and by-product 9%. (UIC 2007c). However, given that the top 5 mines in the world are either open-pit, underground or by-product mines, the decision was made to leave out ISL mines.

MINE	COUNTRY	TYPE	PRODUCTION (tU)	% OF WORLD
McArthur River	Canada	underground	7199	17
Ranger	Australia	open pit	4589	11
Olympic Dam	Australia	by-product/ underground	3388	8
Kraznokamensk	Russia	underground	3037	7
Rössing	Namibia	open pit	2583	6
Arlit	Niger	open pit	1750	4
Rabbit Lake	Canada	underground	1544	4
Akouta	Niger	underground	1403	3
Akdala	Kazakhstan	ISL	1000	2
Zafarabad	Uzbekistan	ISL	(est) 900	2
McClean Lake	Canada	open pit	734	2
Beverley	Australia	ISL	634	1.5
Total			**28,760**	**70%**

Table 5.3 Top 12 uranium mines worldwide

5.4.1.1 McArthur River & Key Lake, Canada

McArthur River is the world’s largest, high grade uranium mine. Discovered in 1988, it is operated by Cameco Corporations but is a joint venture between Cameco Corporation and the AREVA subsidiary, COGEMA Resources Inc. The mine is located 620 kilometres north of Saskatoon, Saskatchewan, Canada. The McArthur River ore body is positioned between 530 and 640 metres underground between dry granite basement rock and overlying water saturated sandstone. The area around the ore-body must be frozen in order to mine safely. The ore is removed by remote control equipment to minimise workers’ exposure to radiation. The mined material is crushed in an underground mill and pumped to the surface as slurry for transportation. The crushed ore from the mine is the loaded in the form of slurry into special containers and trucked to the Key Lake mill over an 80km all-weather road.

The site has an annual production capacity of approximately 18.7 million lbs. U_3O_8, with an average ore grade of 24% U_3O_8, which is approximately 100 times higher than the world average ore grade. The mine has an expected lifetime of 20-30 years and proven & probable reserves in the region of 389 million lbs. U_3O_8. (Cameco 2006a)

McArthur River Model

Infrastructure

As no direct information about the infrastructure of the McArthur River mine was available, the facility was modelled based on a generic underground mine found in the Ecoinvent database, as described in (Dones R. 2003). From this study, the operational lifetime of the mine is taken to be 20 years, while the mine has an ore grade of 0.2% U_3O_8 (0.17% U). The base underground mine has a production capacity of 1.4×10^5 t Ore/year which translates to 2.4×10^2 tU/year. Based on the previous values, an infrastructure factor of 1.766×10^{-7} per kgU_3O_8 (or 1.5×10^{-7} per kgU) was calculated.

Operation

Land take

From the Torness EPD (AEA Technology & British Energy 2005), the McArthur River site covers an area 6.51 km^2 (651 ha.) of which 1.13 km^2 (113 ha.) has been exploited to date for direct mining activities.

Transportation

The transportation of ore between McArthur mine and the Key Lake milling facility is carried out by truck over a 80km all-weather road (Rosner & Edwards 1998) . The ore is crushed underground and ground into a slurry, then pumped to the surface. There the slurry is thickened to a paste that is put into containers and transported by truck 80 km southwest to the Key Lake mill. An average of 8 roundtrips a day are made, each truck carrying 4 containers, and each container holding 5.5 tonnes of ore (Marvin Resnikoff, Kim Knowlton, & Kal Island 1997). Therefore, based on a 28t truck and a transportation distance of 80km, the transportation factor was calculated to be 0.0163 tkm per kg U_3O_8.

Energy requirements

Once again, due to a lack of publicly available data directly from the facility, the energy requirements from the equivalent Ecoinvent entry for the general underground mine were used. It has been assumed that the site is not connected to the Canadian Grid but instead generates its energy on-site. The Ecoinvent database specifies an input of 300 MJ/kgU for an underground mine of average ore grade of 0.2% U_3O_8. Data provided from confidential sources however, indicate that the energy requirements for the extraction of uranium at the McArthur River mine are in the region of 150 MJ_{th}/kgU_3O_8 (130 MJ_{th} /kgU). Given that McArthur River does not have the characteristics of a conventional mine due to its high grade ore , the generic values provided by the Ecoinvent database were adapted to take into account the unique nature of the mine. Thus the values were more in line with the information available in the external sources.

Key Lake Mill

Key Lake, once a mine in its own right, has been milling the ores from McArthur River ever since its own deposits were depleted. Located 570 kilometres north of Saskatoon, Saskatchewan, Canada, it was originally dedicated to open pit uranium mining from 1983 through to the 1990s, but began milling ore from McArthur River in 2000. The mill has an annual production capacity of approximately 18.7 million lbs. U_3O_8, roughly equal to the input from McArthur River mine, to which its operation is linked.

At Key Lake, the ore from McArthur River is blended with "special waste rock" to produce 8500 tU_3O_8/yr (7200 tU/yr). Specifically, mineralized waste rock is also shipped to the Key Lake operation for use in blending down the McArthur River ore to acceptable grades for milling. This ore is blended with McArthur River mineralized waste and Key Lake special waste and contaminated sand in order to reduce the feed grade to 4% U_3O_8 for milling (IAEA et al. 2006). Milling is constrained by licensed capacity, and a planned increase to 10000 tU_3O_8/yr is under review by government agencies and was expected to be implemented in 2009 (UIC 2007b). When milling is complete, the final U_3O_8 product, more commonly referred to as "yellowcake", is packaged into drums and shipped out for further processing to Cameco's Blind River refinery or other facilities, eventually becoming the fuel used in nuclear reactors (Cameco 2006b).

Infrastucture

The milling facilities at Key Lake are modelled using specific data from the site, as cited in the Ecoinvent database literature (Dones R. 2003), and by filling in the gaps using data from the generic database milling facility, where necessary. Based on an output of 4600 tU/year (for 1991) and an estimated operational lifetime of 30 years, the infrastructure factor was estimated to be 6.8×10^{-6} per kgU_3O_8.

Operation

Land use

The values for land use are specific to the Key Lake milling facility as quoted in the Ecoinvent literature. The site uses approximately 2 km^2 for facilities and 0.53 km^2 for mill tailings management.

Water Use

The water use was estimated to be 0.325 m^3/kgU, as quoted in the Ecoinvent database.

Energy requirements

Ecoinvent literature quotes a value in electrical terms of 41 MJe/kgU for an ore grade of 2.4% U_3O_8 (based on data from the time when Key Lake milled its own ore deposits). Data is also provided from the modelling of British Energy's EPD for the Torness Power station (British Energy 2006). As the values provided there are more recent and hence relevant to the milling of McArthur River ore rather than historical data on Key Lake ore, they were chosen for this study. The values from British Energy were found to be roughly twice those calculated by adapting the Ecoinvent entries and therefore provide a more conservative estimate.

Transportation of U_3O_8 in Canada and overseas

Once the uranium has been converted to U_3O_8, the uranium oxide needs to be transported to the conversion site, in this case Port Hope. The transportation is based on the assumption that the uranium oxide is transported by 28t truck by road, over a distance of approximately 3330km (ViaMichelin 2006).

5.4.1.2 Ranger Mine and Mill, Australia

The Ranger mine and the associated town of Jabiru are located about 230 kilometres east of Darwin, surrounded by the Kakadu National Park. The mine started operating in 1980. Full production was in October 1981 at a rate of about 3300 tonnes of uranium oxide concentrate per year. An investment program to increase mill capacity to handle almost 2 million tonnes of ore per year, corresponding to an output of 5000 tonnes U_3O_8 per year from Ranger ore was completed in mid 1997. Since 1996 production has been over 4000 tonnes per year. Uranium recovery rates are high at the facility (about 91.5%, and ranges up to 93%). The following table shows the reserves of the mine, based on (UIC 2007a).

	ORE (milion tonnes)	GRADE $\%U_3O_8$	CONTAINED U_3O_8 (tonnes)
Ranger stockpile	19.81	0.12	23017
Proved & Probable Reserves	12.9	0.22	23738
Total reserves	32.71	0.16	51755
Measured & Indicated Resources	26.49	0.11	29284
Inferred Resources	8.42	0.15	12356
Total Resources	34.90	0.12	41640

Table 5.4 Ranger mine reserves

According to (Solberg-Johansen 1998), in 1995 the average ore grade was 0.3% U_3O_8. This is the value that has been used for the calculations in the modelling. Table B.1 in Appendix B provides an accumulation of the data published in the company's Social and Environmental reports for the period 2001- 2005 (Energy Resources of Australia Ltd 2001) and Solberg (Solberg-Johansen 1998). Where values were not directly available, these have been calculated from other data provided in the reports.

Infrastucture

The infrastructure factors for both the mine and mill were calculated based on the reference mines available in Ecoinvent (Dones R. 2003). Thus, they were estimated to be 5.28×10^{-8} per kgU_3O_8 for the mine and 1.15×10^{-7} per kgU_3O_8 for the milling facility.

Operation

Land use

The values for land use are taken from the 2002 Environmental Statement (Energy Resources of Australia Ltd 2002).It is stated the Ranger mining facilities have disturbed an area of land equal to 5.2 km^2 since the commencement of operation. Specifically, in 2002, 0.18 km^2 of land were disturbed by the activities.

Water Use

Based on the summary of data from the company reports in Table B.1 in Appendix B, the average water use was estimated to be 0.042 m^3/kgU_3O_8 (0.0495 m^3/kgU). This value is supported by data provided in peer-reviewed papers by (Mudd & Diesendorf

2008), where a value of 0.046-0.049 m^3/kgU_3O_8 is quoted. It should be noted that the value from the Environmental Reports is significantly lower than that quoted in the Ecoinvent database, where approximately 1 m^3/kgU is estimated. However, a sensitivity analysis indicated that the use of the value quoted in Ecoinvent would lead to a 0.1% difference in the overall results. Combined with the fact that this value does not appear to be supported by the latest published data, it was thus not used in this research.

Energy requirements

The Ranger mine supplies its own power to both the mining/milling facilities and the township of Jabiru. From the 1995 data, it had a generating capacity of 28MW which were provided by five on-site diesel and one steam turbine driven alternator set. Based on the information available in (Solberg-Johansen 1998), the power requirements of the facilities are in the region 0.018MWh per kgU_3O_8 in 1995. Assuming that this energy is supplied on-site by a diesel electricity generator with a conversion efficiency of 35% (as specified in the Ecoinvent database), the Ranger facilities use an average of 185 GJ/tU_3O_8, which is in-line with the consumption of following years, as estimated from the data in the Environmental reports and summarised in Table B.1 in Appendix B.

5.4.1.3 Olympic Dam Mine and Mill, Australia

Olympic Dam is a multi-mineral ore body, with large reserves of copper, silver, gold and uranium oxides. It is the world’s fourth largest copper reserve and the world’s largest uranium deposit. The ore was discovered in 1975 and operations started in 1988. The mine is located 560km north of Adelaide in southern Australia and is a highly mechanised operation. Olympic Dam has long term contracts for sale of uranium oxide to a number of countries both in Europe and the South East Asia, while quantities are also shipped to Continental America. In 2004, the site processed 9 million tonnes of ore which produced 4,404 tonnes of uranium oxide (BHP Billiton 2006).

The analysis on the Olympic Dam facilities was carried out based on the environmental performance data provided by BHP Billiton / WMC in the reference year of 2004 (WMC Resources ltd. 2005). The data was not product-specific and therefore required manipulation to calculate the values were attributable to the uranium mining operations. A summary of the information is provided in Table 2 in Appendix B, with the last column containing the calculated values attributed to uranium mining.

It should be noted at this point, that according to the data for 2004, uranium production accounted for 1.92% of the total mine products.

Infrastucture

The infrastructure factor for the Olympic Dam mine was calculated based on the reference mines available in Ecoinvent (Dones R. 2003), as no direct data about Olympic Dam was available. As Olympic Dam produces uranium oxide as a by-product of its other mining activities (mainly copper mining), the mine was modelled using a reference non-ferous underground mine as a basis from the Ecoinvent database. It should be noted that the option to model the mine solely as a uranium mine, with an output based on the uranium oxide production of 2004 gave similar results. Based on an annual output of 400000 tonnes of ore per year for the reference mine, and given Olympic Dam's output of approximately 9 million tonnes in 2004, the infrastructure factor for the mine was calculated to be:

8,887,000 t Ore/yr (Olympic Dam) /400,000 t Ore/yr (reference mine) = 22.2

However, given that Olympic Dam's uranium oxide output is less than 2% (1.92%) of the mine's total product output, the infrastructure actually attributable to the uranium mine was estimated to be 0.427. This figure was then divided by the uranium oxide output of the mine for the year 2004, giving an infrastructure factor of 9.7 x 10^{-8} per kgU_3O_8.

The uranium milling facilities were based on a typical uranium mill as modelled in the Ecoinvent database. The uranium oxide production of 4,404 tonnes in 2004 was used to calculate an infrastructure factor 1.15 x 10^{-7} per kgU_3O_8

Operation

As stated above, since Olympic Dam has other products apart from uranium oxide (copper, gold and silver), it would be inappropriate to associate all the resources required for the mine's operation to only one product (namely uranium oxide). This approach was also adopted by British Energy, as evident in the supporting documents to the work carried out for the Environmental Product Declaration (EPD) of the Torness Nuclear Power Power station. Based on WMC estimates, as reported in (AEA Technology & British Energy 2006), it was estimated that 25% of the resources used at the facilities were attributable to the uranium oxide manufacture. It is important to note, that if operating requirements were to be allocated on a mass basis, uranium only accounts for 2% of the mine's total output, as stated previously. However, as there is no information to support the premise that inputs are linearly related to the masses of the mine's products, the conservative estimate of 25% has been used. As a result of the above estimation, all resources were multiplied by this factor for the modelling of the mine/mill, as can be seen in the last column of Table B.2 in Appendix B.

Land use

The values for land use are taken from the WMC Sustainability Website 2004 (WMC Resources ltd. 2005). It is stated that the Olympic Dam mining facilities disturbed an area of land equal to 0.21 km^2 in 2004, of which 0.053 km^2 was attributed to uranium oxide-related activities. Overall, the mine and mill have a land requirement of 1.4 km^2 (1,408 ha). However, only 25% of this area is attributed to the uranium oxide production, as per the rules above.

Water Use

Water requirements at Olympic Dam were reported to be 11,992 million litres in 2004, which gives an allocation of 0.676 m^3 per kgU_3O_8 in that year (WMC Resources ltd. 2005).

Energy Requirements

In 2004, Olympic Dam was reported to have consumed a total of 5,477 TJ of energy (WMC Resources ltd. 2005), which were broken down into the different fuels, as can be seen in Table B.2 in Appendix B. The electricity to the mine is supplied by the Australian National Electricity Grid. Based on the information provided by the IEA's Energy Statistics (IEA 2008a), in 2005 the Australian Grid was supplied by:

	Electricity
	Unit: GWh
Production from:	
- coal	201,087
- oil	1,926
- gas	29,299
- biomass	2,030
- waste	0
- nuclear	0
- hydro	15,886
- geothermal	0
- solar PV	11
- solar thermal	0
- wind	881
- tide	0
- other sources	0
Total Production	**251,120**

Table 5.5 Breakdown of Australian electricity generation for 2005

From Table B.2 in Appendix B, it can be seen that the average energy requirements are of the order of 0.60 GJ_{th}/ t Ore, which is directly comparable with the "direct energy requirements" for ore (0.61 GJ_{th}/ t Ore), as quoted in (ISA 2006).

5.4.1.4 Rössing Mine and Mill, Namibia

Rössing Uranium Limited operates a large open-pit uranium mine located in the Namib Desert, in the Erongo Region of Namibia. The mine is situated close to the town of Arandis, 65 km north-east of the coastal town of Swakopmund. Walvis Bay, Namibia's only deep-water harbour, lies 40 km south of Swakopmund (Rössing Uranium Limited 2004).

Infrastructure

The infrastructure factor for both the mine and mill was calculated based on the reference mines available in Ecoinvent (Dones R. 2003). The values were modified to match the unit of measurement which was per kgU_3O_8 instead of kgU. Thus they were estimated to be 5.28×10^{-8} per kgU_3O_8 for the uranium mine and 1.15×10^{-7} per kgU_3O_8 for the mill.

Operation

Based on the information presented in (Solberg-Johansen 1998), Rössing mine is run using electrically-powered equipment. Haul trucks (which run on electric pantographs) as well as the mining and milling facilities run on electricity supplied by the Namibian Grid. Information about the mine's operations has been collated from the company's Environmental statements (Rössing Uranium Limited 2005) and (Rössing Uranium Limited 2004), (IJG Securities (Pty) Ltd & Smith 2007) and (Solberg-Johansen 1998). From the summary in Table 3 in Appendix B, it can be seen that the mine/mill has higher energy requirements per tU_3O_8 than the Ranger mine, which is to be expected given the lower ore grade, but values comparable to Olympic Dam.

Land use

Since no data was available about the land requirements of the Rössing facilities, the site has been modelled based on the values given in the equivalent process in Ecoinvent (Dones R. 2003).

Water Use

Based on the data compiled in Table B.3 in Appendix B. the average water use over the period 1997-2005 was 0.840 m^3 / kgU_3O_8.

Energy requirements

The Rössing mine, in 1995, was supplied from Namibia's national grid SWAWEK and consumed approximately 154 GWh_e. More recent data indicated that the Rössing mine used approx. 187 GWh_e in 2005. The Namibian grid (in 1995) was made up from approximately 55% Hydro power and 45% coal power. Using more recent data provided by the IEA's Energy Statistics for Namibia (IEA 2008b), the country's electricity production mix is:

Electricity	*Unit: GWh*
Production from:	
- coal	6
- oil	45
- hydro	1,658
Total Production	**1,709**
Imports[1]	1,567
Exports	-78
Domestic Supply	**3,198**

[1] imports from S.African Grid

Table 5.6 Namibian electricity mix

As can be seen in the above table, the Namibian Grid, imports substantial amounts of electricity from the neighbouring S.African Grid. The breakdown of that Grid is shown below:

	Electricity
	Unit: GWh
Production from:	
- coal	228,601
- oil	0
- gas	4
- biomass	259
- waste	0
- nuclear	11,293
- hydro	4,199
- geothermal	0
- solar PV	21
- solar thermal	511
- wind	32
- tide	0
- other sources	0
Total Production	**244,920**

Table 5.7 Breakdown of S. African electricity mix

Table B.3 in Appendix B. shows that the energy requirement data from (IJG Securities (Pty) Ltd & Smith 2007) and (Solberg-Johansen 1998) are slightly higher than what is reported in the mine's 2004 Stakeholder Report (Rössing Uranium Limited 2004), but the overall trend is fairly constant, giving a value of 390 GJ_{th}/ tU_3O_8. However, in this work the value for the year 1995 has been used, in order to provide a conservative estimate of electricity use at the facilities.

5.4.2 Conversion

The conversion process for this study is assumed to be undertaken at three different facilities. The uranium ore processed at Key Lake mill, Canada, is assigned to the conversion facility at Port Hope (also in Canada), while the uranium milled at the other mines in the study (Australia and Namibia) is assumed to be shipped to Europe for conversion. In reality, the yellowcake from Key Lake is transported to the refinery at Blind River, where it undergoes a conversion to an intermediate stage (UO_3). This product is then transported to Port Hope for final conversion to UF_6 and UO_2. However, as this additional step is only used for this particular supply route, and the conversion process modelled here is based on generic data (that includes all stages from U_3O_8 to UF_6 production) rather than site-specific data, this extra step has been ignored from the modelling. Depending on the proposed enrichment procedure to be subsequently followed (by centrifuge or diffusion), the U_3O_8 is shipped to either the United Kingdom or France. If the centrifuge enrichment process is chosen, the U_3O_8 is transported for final conversion to the U.K. at the Springfields facility. If however, enrichment is to be carried out using the diffusion process, the yellowcake is taken to the conversion facilities at COMURHEX Malvesi/Pierrelatte.

As such, two separate supply routes were set up in the modelling, one that directs all shipments of U_3O_8 to the United Kingdom where they are converted and (with the addition of the UF_6 from Canada) are enriched centrifugally, and the other where the shipments are sent to French facilities for enrichment through the diffusion process.

It should be pointed out that, as there was not enough data available about the operations at any of the conversion facilities, the analysis of the conversion stage was carried out using the generic model available in the Ecoinvent database (Dones R. 2003).

The Port Hope facility is the only uranium conversion facility in Canada and one of only four in the western world. It has the ability to produce both uranium hexafluoride (UF_6) as well as uranium dioxide (UO_2) for fuel assemblies. Port Hope was originally used as a radium extraction site with uranium being a side-product, but went on to produce UF_6 for light water reactors in the 1970s. The site has an annual capacity of 12,500 tonnes UF_6 and 2,800 tonnes UO_2 (Cameco 2007).

The Springfields Facility in the United Kingdom produces uranium metal fuel for the MAGNOX fleet of reactors and uranium dioxide for the AGR and PWR fleet. The plant also has facilities for the conversion of uranium "yellowcake" to uranium hexafluoride (UF_6). Some data for the site was sourced from (Solberg-Johansen 1998), where it was stated that the for the conversion procedure, the electricity consumption was approximately 95.7 GWh_e, while the facility produced 8.88 million kg of UF_6. This is in line with the value used in the conversion model in Ecoinvent (Dones R. 2003).

The COMURHEX Malvési plant in France, purifies uranium ore concentrates to a very high degree, before performing the first stage of fluorination, in order to obtain UF_4. The second fluorination stage, transforming UF_4 into UF_6 (uranium hexafluoride), is carried out on site at COMURHEX Pierrelatte. COMURHEX Pierrelatte converts uranium tetrafluoride (UF_4) into uranium hexafluoride (UF_6). COMURHEX also produces UF_6 from reprocessed uranium arriving from the facility in The Hague (AREVA 2008a). The Pierrelatte site is powered by the Tricastin nuclear power plant (which also powers the enrichment facility), while the Malvési plant is assumed to be powered by the Grid. Due to the lack of distinct data, the conservative assumption has been made that both are powered by the French national grid. As such, this should not unduly bias the results as the grid mix in France itself contains a very high proportion of nuclear generation (approximately 75% in 2009) (World Nuclear Association 2009).

Transportation of U_3O_8 from Australia to conversion facilities in Europe

The U_3O_8 milled at the Olympic Dam and Ranger facilities is transported by oceanic tanker to the conversion facilities in Europe, where it undergoes the conversion to UF_6. The distance covered by tanker is in the region of 6,500km for the Ranger mine, and 17,600km for Olympic Dam (SeaRates 2008).

Transportation of U_3O_8 from Namibia to conversion facilities in Europe

The U_3O_8 milled at the Rössing facility is assumed to be transported by oceanic tanker to Europe where it undergoes the conversion to UF_6. The distance covered by tanker is in the region of 10,100km (SeaRates 2008).

It is to be noted that transportation during operation is covered by the module, and is based on the facilities at COMURHEX at Malvesi and BNFL Springfields, as stated in the Ecoinvent literature (Dones R. 2003)

5.4.3 Enrichment

As mentioned in the previous stage, depending on the final enrichment procedure to be used, the UF_6 nat. that originated in the U.K., French and Canadian conversion facilities, is processed in enrichment plants, either in France or the United Kingdom. The two countries offer different enrichment methods, with the U.K. using a gas centrifuge process based at Urenco Capenhurst, while shipment enriched in French facilities are assumed to be subjected to the gas diffusion method at the Eurodif Tricastin facility. A brief description of the two facilities is made below.

Urenco Capenhurst

Urenco Capenhurst, in the United Kingdom, is a enrichment facility based on the gas centrifuge process. It operates at the Capenhurst site, which is jointly occupied with British Nuclear Group Sellafield Limited Capenhurst, near Chester in the UK. Urenco also has other enrichment facilities at Almelo in Holland and at Gronau in Germany. Data about the facility’s operations has been taken from the company’s Sustainability Reports (Urenco Ltd 2008), the Capenhurst site Health and Safety and Environment Reports (Urenco Ltd. 2006), as well as from the Ecoinvent reports on the nuclear fuel cycle which in turn was based on Urenco Gronau’s Environmental Statement for 2002 (Urenco Deutschland GmbH 2002).

Infrastructure

As the facility modelled in the Ecoinvent database is directly based on Urenco Gronau, no changes were required to the infrastructure factor for this research.

Operation

Land use

The actual enrichment process itself does not require the sequestration of any land apart for the actual siting of the plant. As previously mentioned, the site has been modelled based on the values given in the equivalent process in Ecoinvent (Dones R. 2003).

Water Use

Based on the data provided in (Urenco Deutschland GmbH 2002), the average water use over the period 1991-2001 ranged between 0.002 and 0.007 m^3 per SWU. A conservative value of 0.004 m^3 per SWU was used for this study.

Energy requirements

From the information provided in Urenco’s Sustainability report, the site’s electricity requirements averaged at approximately 50 kWh_e/ SWU, with Gronau reporting a demand of 36 kWh_e/ SWU (Urenco Deutschland GmbH 2002). In this work, it is assumed that the requirements are closer to the lower estimates (allowing for future improvements in operations), and are set at 40 kWh_e/ SWU. The previously mentioned report also details the diesel and natural gas requirements for the site, giving values of 0.02 l/ SWU and 0.3 m^3/ SWU respectively, which match the entries in the Ecoinvent database. It should be noted, that in Vattenfall’s EPD for the Forsmark power station (Vattenfall AB Generation Nordic Countries. 2004), it is claimed that the Urenco facilities in the U.K. are no longer supplied by the National Grid but solely from electricity produced by nuclear power. This would mean that the emissions from this process in the lifecycle would be lower still. However, as the author was unable to verify this piece of information, the process in this study was modelled assuming the National Grid supplied the electricity to the enrichment facilities, thus providing a conservative estimate.

Eurodif Tricastin

The EURODIF Production plant, named "Georges Besse", is located on the Tricastin nuclear site between Drôme and Vaucluse, France. It enriches uranium for some 100 nuclear reactors in France and throughout the world. The enrichment process used by EURODIF Production is gaseous diffusion: uranium hexafluoride (UF6) in gaseous state is pushed via compressor through a cascade of diffusers containing porous diffusion barriers. This process is repeated 1,400 times in order to produce enriched uranium suitable for nuclear reactors (3% to 5%) (AREVA 2008b). The site also contains 4 nuclear reactors, rated at approximately 915 MW_e each, which produce electricity for the French Grid, but also supply all the electricity requirements of the facilities on-site.

The Ecoinvent database contains an entry modelled directly on the Eurodif facilities in France, therefore providing an accurate description of this phase of the fuel cycle. The values given in the database entry were compared with other literature for the sake of verification. (ISA 2006) states that the average energy requirements for gas diffusion plants, are in the range of 2600 kWh_e/SWU, which are directly comparable to the Ecoinvent entry.

Transportation of UF_6 for the Centrifuge Enrichment process

The UF_6 produced at the Springfields conversion site is assumed to be transported by road to the enrichment facilities at Urenco Capenhurst, a distance of 70km (ViaMichelin 2006). UF_6 shipments from the Port Hope conversion facility in Canada, is first transported by tanker to Europe an average distance of 6,500 km (3500 naut. miles) (SeaRates 2008), and then 40km overland from an assumed berthing in Liverpool to Capenhurst (ViaMichelin 2006).

Transportation of UF_6 for the Diffusion Enrichment process

In the case that the gaseous diffusion method is adopted, the UF_{6nat} produced in Canada is shipped to Europe as above, but then diverted to Calais, France. From there is it shipped to the Tricastin site by road, a distance of 930km (ViaMichelin 2006). U_3O_8 shipments from Australia and Africa, are assumed to have first been sent to the conversion facility in Malvési/Pierrelatte, which is co-located with the Tricastin enrichment plant.

5.4.4 Fuel fabrication

For the purposes of this study, the fuel fabrication stage is assumed to be carried out at the BNFL Springfields fuel fabrication plant in the United Kingdom. As also seen in earlier stages, both conversion and fuel fabrication are carried out at the same location. With respect to the fuel fabrication stage, the facility produces both uranium metal oxide for Magnox reactors and uranium dioxide fuel for AGRs and PWRs.

Operation

As in the other stages, the Ecoinvent module has been used to simulate this stage due to the lack of a complete dataset. There is however generic operational data about similar facilities available from a IAEA publication (IAEA 2002) that used the Lingen Advanced Nuclear Fuel GmbH (ANF) plant as a case study. Based on this report, a typical stand-alone fuel fabrication plant has the following requirements:

FUEL FABRICATION PLANT	
Production (t UO_2/yr)	400
Fuel Fabrication Energy Consumption	
Thermal Inputs (MJ_{th}/ kg U)	34
Electrical Input (kWh_e/ kg U)	25

Table 5.8 Fuel Fabrication Facility Data

The thermal inputs are only specified as “fuel and hydrogen” in (IAEA 2002). Comparing these values above to the thermal inputs described in the Ecoinvent model, they are almost identical to those quoted above, whereas the quantity of electricity used is higher, probably reflecting the difference in age of the data (Ecoinvent set is older and gives 36 kWh_e/kgU). (Solberg-Johansen 1998) contains a brief description on the Springfields site. However, she reports a significantly lower value for the electrical input, giving 8.1 kWh_e /kgU.

Another point of note with regards to this stage, is the approach taken to modelling zirconium alloy. As mentioned above, zirconium alloy, also known as zircalloy, is used as the cladding for UO_2 pellets. Zircaloy is an alloy of zirconium (98%), tin (1.5%) and small amounts of iron, nickel, and chromium. It does not absorb neutrons, is very resistant to corrosion, and it withstands high temperatures, all of which makes it particularly suited for deployment in nuclear reactors (Vattenfall AB 2004a).

The Ecoinvent module, which was used to model this stage, does not contain an appropriate entry for this alloy which according to the relevant Ecoinvent report (Dones R. 20087) is not considered to represent a substantial input to the process in any case. Based on this assumption, the alloy has been modelled using Chromium as a substitute. Closer inspection of Chromium reveals that it has an embodied energy approximately 590 GJ $_{pr}$/t, while according to (White 1998), zirconium has an embodied energy of 1610 GJ_{pr} /t. As such, it has been necessary to create a new entry based on the Chromium entry but with the embodied energy requirements multiplied by an appropriate factor. It is felt that this provides a more robust representation of zirconium alloy in the lifecycle.

Transportation of UO_2

The calculations for this stage include the transportation of the enriched UF_6 from the Capenhurst plant back to Springfields (approximately 13 km) for the UK shipments, and also the transportation of the shipment from Tricastin to the harbour of Calais in the north of France by truck (estimated at 500 km), the transportation by ship of the fuel over the Channel from Calais to Dover/Folkestone (680 km) and the final distance between Dover/Folkestone to Springfield by truck (460 km).

The final process related to this stage is the transportation of fuel from the fabrication plant to the nuclear power station. The distance is of the order of 416 km from Springfields to Sizewell by road(ViaMichelin 2006).

Land Use

The area used is based on the values for the Springfields site in the U.K. As this site covers the stages of fuel fabrication and conversion however, the area allocated to this stage is also considered to encompass the conversion facilities, previously mentioned in this life-cycle. As a result, the area attributed to the conversion and fuel fabrication facilities is of the order of 60 hectares (Sustainable Development Commission 2006c).

5.5 Nuclear Power Station construction and operation

The nuclear power station module in SimaPro has been modelled in two components: the first component covers the actual construction of the NPP, including the transportation of components from the manufacturing facilities and the on-site assembly, while the second component encompasses the inputs and outputs related to the actual operation of the nuclear power station. As stated in previous sections, the power plant is based on the proposed Gen. III+ designs, being considered for construction in the United Kingdom. Data sources on the material requirements of new nuclear power stations is limited, so it was necessary to use information that was not “reactor-specific” for this stage. However, it has been assumed that due to the many commonalities in the PWR designs, the generic data would be applicable to all the designs being considered in the U.K. The operational characteristics of the power plant were based on the published data for the AP1000 reactor, as will be described in the following sections.

5.5.1 Nuclear Power Plant Construction

The power plant construction phase is one of the most difficult to model, due to the lack of substantial data for this phase of the life cycle. As a result, this stage is commonly simulated using economic data and energy intensities of processes/sectors, using I/O methodology or other hybrid techniques. Values for power plant construction vary between 1,177 and 29,722 GWh_{pr} per GW_e (4.02 – 107 PJ_{pr} per GW_e) and are highly dependant on the year of construction and the method used for energy accounting (ISA 2006).

Discarding the values provided by Input/Output methods for the reasons outlined in the methodology presented Chapter 3, the phase was modelled using data for construction of a nuclear reactor that was analytical as possible. Information sources with this level of detail however are extremely limited. Despite this drawback a few published studies contain detailed information on the quantities of materials used in the construction of a NPP and have been compiled in (Storm van Leeuwen 2007). The values in that report are presented in Table B.4 in Appendix B, together with data collected from other reports. Some values have been modified, where necessary, for consistency.

(Storm van Leeuwen 2007) also indicates the existence of another study, from 1982, that contains data on the required steel mass but does not contain information on the concrete requirements and has, as such, been omitted from the above table. From the data presented there, it can be seen that the first two columns contain practically identical entries for all materials, indicating that they are using the same database. The data from newer studies shows an increase in the concrete/steel ratio, as well as a steady increase in the total mass of the materials used to construct the nuclear power plant. As many newer designs claim to have a reduced "footprint", it is extrapolated that the increase in the concrete/steel ratio is not indication of more buildings as such, but an increase in the amount of containment structures, employed in modern reactors. In this study, the values from the last column were used, since they are believed to be the most representative of the modern class of reactors being put forward by companies.

Nuclear power plant construction supply chain

A study by IBM (IBM Business Consulting Services 2005). on UK and global capabilities to support a round of new nuclear build indicated that whereas the UK has significant capabilities in certain areas, in other key areas the UK alone would not have the prerequisites to meet the demands for new nuclear build. Specifically, it was stated that "*the UK supply chain would be unable to deliver a new build programme alone, and therefore support from the global supply chain will be required. In particular overseas input will be needed to provide the reactor design, reactor pressure vessel, low alloy forgings and turbine generators*" (IBM Business Consulting Services 2005). It also went on to point out that the scale of the role played by the UK supply chain will be determined to an extent by the consortium structures and the choice of reactor design. Since none of the reactor designs are "indigenous", the possibility exists that a design owner may have existing global supply chain arrangements, which may limit the level of participation of the UK supply chain in a new build programme. Although the report does not give specific data or examples of shortcomings of the UK supply chain, from graphs in the report, it appears that the UK would be lacking in most of the critical component manufacturing capabilities (e.g. primary circuit pressure vessels, ring-forgings, turbine generators and reactor pressure vessels), as well as in the staff with the skill an experience required to manufacture, construct and operate such facilities. A similar study was carried out by the U.S. Department of Energy for their NP2010 program, which identified similar problems for a potential new round of U.S. nuclear power (DoE 2005). However, the only major shortcoming with respect to components/manufacturing capabilities was found to be the availability of ring forgings.

As such, a comparison would seem to indicate that the United States are better suited to provide the components required by a new nuclear build programme. As a result and for the purposes of this research, it has been assumed that the major components of the NPP design will be manufactured overseas and transported to the UK for final assembly.

Component Transportation

As part of the evaluation of the NPP construction it was necessary to take into account the transportation requirements for the different power plant components. This was especially relevant since the different modules are to be manufactured in the Westinghouse facilities in the United States, for final assembly on-site in Sizewell in the United Kingdom.

One of the main characteristics of this next generation PWR design, as proposed in almost all GEN III+ designs and specifically the AP1000, is that of modularity. By creating separate building modules, construction times are reduced, since work on different modules can be carried out in parallel, while assembly is also simplified. From the company website, the company's main manufacturing facilities are located in Pennsylvania, New England, South Carolina and Utah. Based again on company information, the AP1000 reactor can be broken down into large modules and 250 smaller ones (80 tonnes each), which are rail shippable. As a result, in this study the 250 modules are shipped by train to U.S. ports and transported by ship across the Atlantic and then again by train to the final site. It is believed that the larger components are manufactured closer to the ports (Pennsylvania, New England, South Carolina) for easy transportation and hence the pre-oceanic transportation distances have been assumed negligible. The smaller rail shippable units are modelled to have been manufactured in Utah, as it is the facility furthest from the port on the eastern seaboard.

From the information provided about the design, the 250 modules (at a weight of 80t each) are shipped by rail across the United States, from the company facilities in Utah to the port of Portland, on the Atlantic Coast. The distance has been estimated to be approximately 3000 km. Once the all the NPP components and modules are located at ports on the eastern seaboard, they are loaded on transatlantic freight ships and shipped to port of Felixstowe in the United Kingdom, the most common destination for large U.S. freight. From this location, the 250 rail-shippable modules are sent by rail, the distance of 65km to Sizewell, while the rest of the reactor's materials and components are transported by barge/freighter to the final assembly site. For the purposes of the study, the distance used for the barge transportation was again taken to be 65km.

Construction Energy

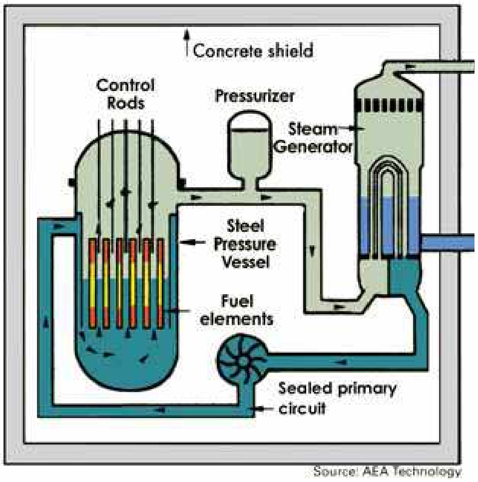
The information inputted up to this point to the NPP construction model, encompasses all the energy requirements for the manufacture of the materials as well as those for transportation of the finished products. However, there is also a substantial input to the construction process in the form of construction energy of the components and of the assembly of the actual power plant. This input takes the form of building equipment used for the construction as well as fossil fuel and electricity inputs. Due to the nature and scale of the undertaking, no detailed and very little circumstantial information is available. The Ecoivent database information is based on the construction of Swiss PWR during the 1980s. However, the inputs were aggregated with the energy required to decommission the plant at the end its life, so it was necessary to calculate the correct proportion of energy to attribute to the construction. Other sources of data on the construction phase are summarised in (Storm van Leeuwen 2007). Another source of data is available in (White 1998) which in turn is based on (Tsoulfanidis 1981). However, all these sources use the I/O methodology to establish the energy requirements. In order to maintain consistency with the other stages of the life cycle, the Ecoinvent inputs were utilised instead. The possibility that the data might be too project-specific (i.e. only applicable to the Swiss PWR) was considered but checks indicated that the similar values were also assumed in the Ecoinvent database for other national reactors (i.e. german), indicating that the value was of a more generic nature. The information is given in terms of diesel requirements, which is assumed to be used in construction equipment, while the electricity is supplied by the National Grid. There is also an input of light fuel oil, which was used for the operation of the turbines in the plant.

Finally, it needs to be highlighted that the environmental impacts of on-site activities associated with this stage of the NPP life cycle, have not been included as there was no published data to cover this aspect.

5.5.2 Nuclear Power Plant Operation

Brief Description of the reactor core

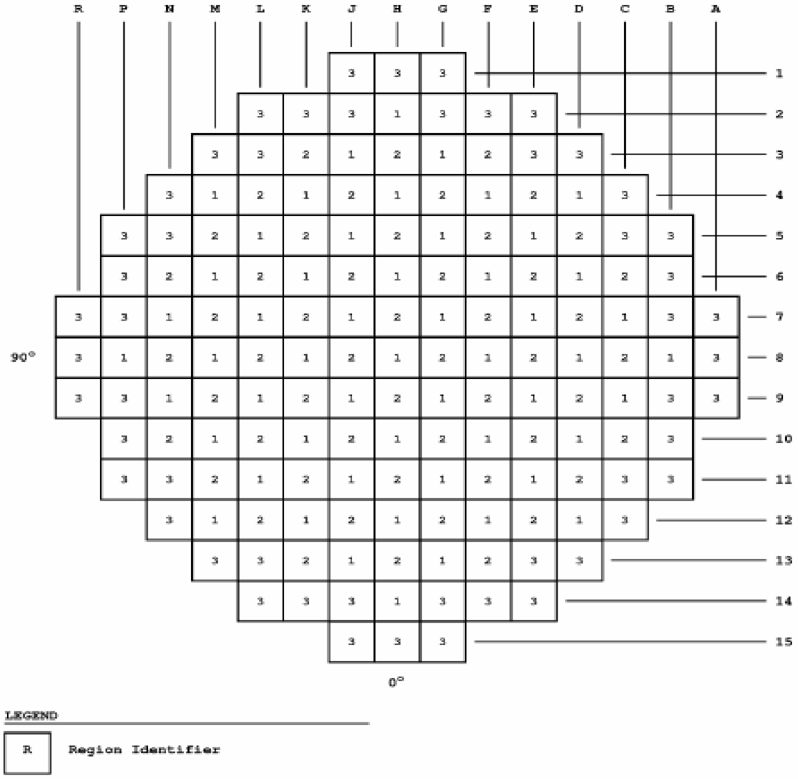
As mentioned previously, the type of reactor under investigation in this work is based on the Pressurized Water Reactor (PWR). Figure 5.2 provides a schematic of a PWR (taken from (Vattenfall AB 2004a):



Source: AEA Technology

Figure 5.3 Schematic of a generic PWR

The amount of fuel (UO_2) in a full reactor core is given by the relevant literature, as approximately 96 tonnes (211588 lb), while the reactor core itself consists of a specified number of fuel rods held in bundles by spacer grids and top and bottom fittings. The bundles, known as fuel assemblies, are arranged in a pattern which approximates a right circular cylinder. Each fuel assembly contains a 17 x 17 rod array composed nominally of 264 fuel rods, 24 rod cluster control thimbles, and an in-core instrumentation thimble. An example, taken from (Westinghouse Electric Company LLC 2007), is shown in Figure 5.3.



	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							3	3	3						
2					3	3	3	1	3	3	3				
3				3	3	2	1	2	1	2	3	3			
4			3	1	2	1	2	1	2	1	2	1	3		
5		3	3	2	1	2	1	2	1	2	1	2	3	3	
6		3	2	1	2	1	2	1	2	1	2	1	2	3	
7	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3
8	3	1	2	1	2	1	2	1	2	1	2	1	2	1	3
9	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3
10		3	2	1	2	1	2	1	2	1	2	1	2	3	
11		3	3	2	1	2	1	2	1	2	1	2	3	3	
12			3	1	2	1	2	1	2	1	2	1	3		
13				3	3	2	1	2	1	2	3	3			
14					3	3	3	1	3	3	3				
15							3	3	3						

Region	Enrichment
1	2.35 w/o
2	3.40 w/o
3	4.45 w/o

Figure 5.4 Typical Loading arrangement

Fuel consumption and core management

As mentioned in previous sections, when a neutron is absorbed by a fissile nucleus, the nucleus may split into two lighter nuclei with an accompaniment of beta and gamma rays, more neutrons and energy. The energy released is equivalent to the mass lost in the fission process, since the produced nuclei will weigh slightly less than the original nucleus they came from. The amount of energy released from the fission of a nucleus is of the order 3.2 x 10^{-11} J, which although small, is massive compared to the mass involved (Rahn, Adamantiades, Kenton, & Braun 1984). Therefore, it possible to calculate the amount of energy released, usually expressed in terms of MWd (MegaWatt days), per unit mass of fuel, expressed in terms of heavy metal (HM: only U, Pu, etc, without the oxyde and structural material weight of fuel rods and elements), called the burn-up. Fuel burn up is a measure of fuel depletion which represents the energy output of the fuel in megawatt-days per metric unit mass and is a useful means for quantifying fuel exposure. Put simply, the reactor power multiplied by the irradiation time (the time the fuel remains in the reactor) equals the thermal energy generated in the reactor in that period. There is an economic incentive to increase the burn up ratio, as this generates as much energy as possible for a given quantity of fuel, thus reducing the unit cost of fuel fabrication and the quantity used throughout the life cycle. Higher burn up rates can be achieved by increasing the fuel enrichment.

From the above it is obvious that as fuel is burned, a point is reached where the reactor can no longer remain critical (i.e. retain a chain reaction), even if the control rods are completely removed from the reactor. At that point, the reactor operator must implement changes to the reactor composition, in order to restore the chain reaction. The procedures undertaken include replacement of part of original reactor fuel with new batches at preselected time intervals, movement of existing fuel batches from one position in the reactor to another and varying the composition of the new fuel with respect to the level of enrichment.

This means that not all the reactor is replaced at the same time. As a rule of thumb, approximately a third of the reactor is replaced at each interval, together with a reshuffling the remaining fuel to achieve optimal safety, economics and burn-up of the core in subsequent cycles. For this study, it assumed that the reactor refuelling occurs at 18 month intervals, as quoted in the relevant AP1000 literature. In general, the operator tries to operate the fuel as close as possible to its thermal limits for as long as possible, without incurring fuel failures, while achieving as uniform a burn up as possible in the reactor (Rahn, Adamantiades, Kenton, & Braun 1984).

A distinction has to be made between the “initial cores” and the subsequent “reloads”. An initial core refers to the first loading of fuel into a newly constructed reactor which is embarking upon its first operating cycle. A reload on the other hand refers to the refuelling of that reactor, which normally occurs 12/18/24 months following the start of subsequent cycles. However, initial cores and reloads do not have the same level of enrichment. Initial cores, usually have lower enrichments than subsequent reloadings, in order to achieve the proper criticalities in the reactor (Melbye 2007). For initial core loading, the fuel rods within a given assembly have the same uranium enrichment in both the radial and axial planes. Fuel assemblies of three different enrichments are used in the initial core loading to establish a favorable radial power distribution. Two regions consisting of the two lower enrichments are interspersed to form a checkerboard pattern in the central portion of the core. The third region is arranged around the periphery of the core and contains the highest enrichment. Values for the AP1000, state that the enrichment levels of the three different regions are 2.35%, 3.4% and 4.45%. Reload core loading patterns can employ various fuel management techniques including “low-leakage” designs where the feed fuel is interspersed checkerboard-style in the core interior and depleted fuel is placed on the periphery. The exact reloading pattern, the initial and final positions of assemblies, and the number of fresh assemblies and their placement are dependent on the energy requirement for the reload cycle and burnup and power histories of the previous cycles (Westinghouse Electric Company LLC 2007).

For this work the initial core enrichment has been taken 3.4%, with an initial reloading occurring at 18 months. Subsequent reloads are assumed to have an average enrichment of 4.95%. For the initial core, the power station’s load factor has been defined as 75%, rising to an average 85% after the initial 18 months. Based on these assumptions, burn up rated of 16.4 MWd/ kg U were achieved with the initial core, rising to 48 MWd/ kg U for the rest of the station’s operational lifetime.

Nuclear Power Plant Operation modelling

The operational stage of the nuclear life cycle stage is one of the most contentious, as this stage of the life-cycle has low associated CO_2 emissions, especially when compared to conventional fossil-fuel burning power plants. Thus it is highlighted by supporters of nuclear power in order to promote the fuel cycle's environmental credentials. There is however a considerable range of estimates in the actual energy requirements attributed to the reactor, as discussed in previous parts of this report.

Energy inputs for operation

The energy requirements for operation include not only direct energy inputs (such as electricity and fossil fuels) but also the energy of any material inputs (such as metals, cement/concrete, gases etc), required for the operation of the power plant. Normally, these two different input streams would be presented separately, confirming to international guidelines on energy assessment. In order to be able to compare the values with other studies reviewed in the literature review in Chapter 2 however, the energy requirements were aggregated.

There appears to be significant differences for this life cycle stage, between industry and academic values. An example of this can be seen in the information quoted by the World Nuclear Association in their energy analysis (WNA 2005a) concerning Vattenfall's EPD for the Forsmarks NPP, where a value of 0.0275 PJ/ year (direct primary energy i.e. does not include indirect energy requirements, but combined electrical and thermal inputs) is attributed to operations at Forsmarks power station. In the 2004 version of the EPD for the same power station, Vattenfall has a value of 0.083 PJ / year (Vattenfall AB Generation Nordic Countries. 2004). By comparison, the average from 8 studies on PWR operational requirements included in the report by the University of Sydney, is approximately 1.01 PJ_{pr}/ GW_e per year (280 GWh_{pr}/ GW_e per year) (ISA 2006), with values ranging from 0.284 – 3.2 PJ_{pr}/ GW_e per year (79 - 889 GWh_{pr}/ GW_e per year) of operation. The discrepancy can be partly explained by the fact that all the higher values are based on I/O methodology which usually produces higher values since it tends to include more background processes, and partly by the fact that the academic values are total (primary) energy values so include both direct and indirect energy inputs.

For the modelling of this stage, the Ecoinvent database entry was used, but modified where necessary. The Ecoinvent module was based on actual performance data from German reactors during the period 1991/2. Although it could be argued that the information might be considered dated, this was the most up-to-date publicly available data. The power plant provides for its own electrical needs (therefore no electrical input is required for this process), and therefore there has been a reduction in the capacity rating of the reactor (from 1117MW_e to 1090MWe as stated in (Cummins, Wright, & Schulz 2000)) to reflect this fact. This means that the on-site electrical requirements are in the region of 27MW_e. This value is lower than the equivalent one for Sizewell B (70MW_e as quoted by (Mcnamara & British Energy 2006)), but this could easily reflect the reductions quoted in the number of pumps and other equipment in the new reactor designs. The rest of the direct energy inputs are assumed to reflect fuels required during for start-up and power outages, as well as maintenance and core-refuelling procedures. Using these assumptions, the aggregated direct energy use for this section has been calculated to be approximately 0.033 PJ_{pr}/ year (or 0.030 PJ_{pr} /GW_e / year) .

Land requirements for operation

The value used for this study was 1 km^2, which it at the lower end of the range of the values (1- 4 km^2) given in (Sustainable Development Commission 2006c). This choice was based on quotes from literature, that the GEN. III+ reactor would have a reduced footprint compared to current PWR designs (Energetics Incorporated 2005). Figure 5.4 gives an illustration of this, taken from (Vande Putte D. & NIREX UK LTD 2004)

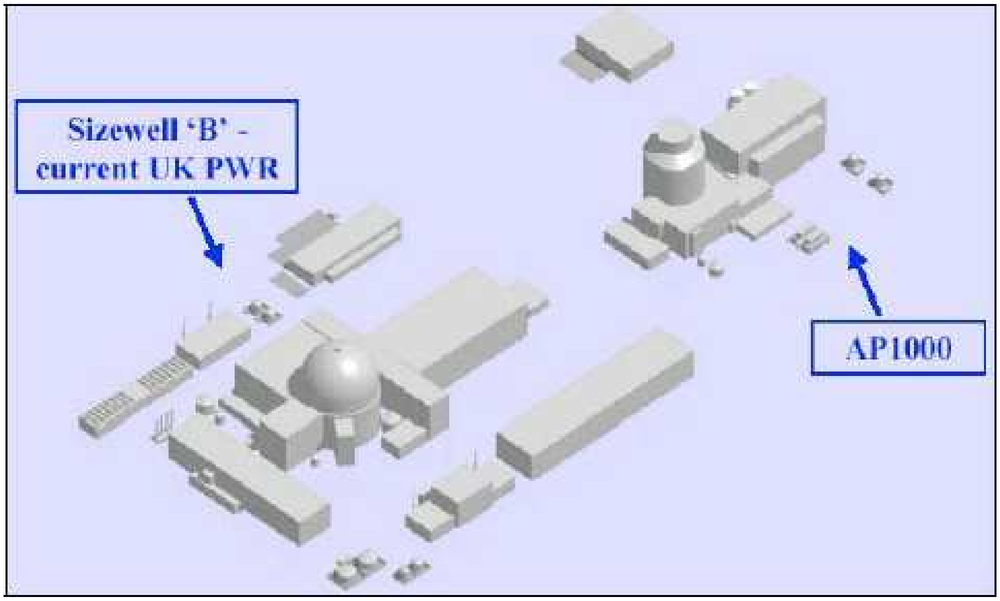


Figure 5.5 Size comparison of the AP1000 to Sizewell B

It should be noted that in (Westinghouse Electric Company LLC 2007), it is stated that the entire facility will be within an area of 25 acres, which translates to 0.1 km^2. However, as this value is significantly below the values quoted above, it was not deemed credible.

Water use for operation

Nuclear power plants use substantial amounts water during operation. This water is mainly used as a reactor coolant, meaning the power plants have to be situated near a water body, usually the sea. (Sustainable Development Commission 2006c) claims in survey of the nuclear fuel cycle that based on results from published sources, a value of 40 m^3 per second of water is not untypical for older reactors. This value is echoed in reports such as (Feeley III, Skone, Stiegel, McNemar, Nemeth, Schimmoller, Murphy, & Manfredo 2008) have values of 0.119 m^3 per kWh (which using this assumption for the modelled reactor in this work would give 31.4 m^3 per second) for a once through water cycle while (Inhaber 2004) has a value of 38 m^3 per second. However, both reports point out an important distinction; "Water withdrawal represents the total water taken from a source, while water consumption represents the amount of water withdrawal that is not returned to the source" (Feeley III, Skone, Stiegel, McNemar, Nemeth, Schimmoller, Murphy, & Manfredo 2008). Using the value for water consumption from that report gives 0.00052 m^3 per kWh, which converts to 0.13 m^3 per second. Other reports however, such as (von Uexküll 2004), quote significantly higher values, in the region of 0.84 m^3 per second (which is based on a value of 0.002 m^3 per kWh). From the description in the latter report, this value covers the actual water lost in the cooling towers. This difference of several orders of magnitude in the values quoted by the different reports would seem to indicate that the higher values actually represent water withdrawal, whereas the lower ones water consumption (and hence do nor include the water sequestered from the water source but otherwise returned at the end of the cycle). The value used in the Ecoinvent entry is based on actual power plant figures and is approximately 8 kg per kWh, which translates to 0.008 m^3 / kWh, or 2.1 m^3 per second. As the purpose of the study is to highlight water use from a "resource depletion" point of view, it was felt that the Ecoinvent entry provided a conservative estimate for the modelling of this stage.

5.5.3 Load factors for U.K. nuclear power plants

The load factor of a power plant can generally be described as the ratio of the amount of power produced by a generator, divided by the engineering capacity of the unit. Usually load factors are calculated for a year. The calculation, then, is formulated as the total kilowatt hours (or multiples) of energy generated by the unit, divided by the capacity of the unit in kilowatts, multiplied by the number of hours in the year (Maloney 2003).

The capacity factor of the U.K.'s nuclear power plant has become a heated issue in recent years, due to the failure of many of the old plants to maintain constant operations. The examination of the load factor of existing power plants is pertinent, as many sources claim that Gen. III+ reactors will have an operational lifetime of the order of 60 years, at a capacity factor as high as 90%. As load factors play an important role in the calculation of almost all critical life-cycle parameters (both energetic and economic), it is necessary to test these claims against recent experience.

Nuclear power plant capacity factors worldwide, tend to run at a fairly constant output (as a result of the need to run the reactors at a constant loading) throughout the operational life, with the exception of breakdowns as the plants near the end of their operating life. (Maloney 2003) provides data that illustrates that, historically in the U.K., load factors for nuclear reactors have been in the region of 67%, with load factors since 1996 averaging at 74%. Based on more reliable data, as published in (DTI 2007a), the 10 year average load factor for UK nuclear power plants was calculated to be 75.1% for the period 1996-2006. A detailed yearly breakdown of load factors can be seen below, in Table 5.9:

Plant load factor											
Unit	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Per cent	76.5	79.1	80.1	77.5	70.5	76.1	75.1	77.8	71.8	72.4	69.3

Table 5.9 Load factors for U.K. nuclear power plants 1997-2006

From the above table, during the last 10 years, UK nuclear power plants have not achieved load factors above 80%. However, Sizewell B achieved 91.5% load/capacity factor in 1996 according to (Meyer & Stokke 1997) but this seems to have been a fairly limited case. NIREX, as presented in (Vande Putte D. & NIREX UK LTD 2004), have used a capacity factor of 83% in their estimates of the wastes from new nuclear reactors.

Another source of assumptions on the load factor of future designs, are studies into the economics of nuclear power. The WNA for example, in their economic analysis of nuclear power (WNA 2005b), state that capacity factors of nuclear plants around the world have increased by ten percentage points since 1990, from 70% to 80%. In certain countries, such as the United States, the improvement is even more dramatic, with an increase from 66% to 90%. Levels of 90% and above have also been achieved by many plants in Europe and Asia for many years. The University of Chicago study, published in 2004, uses a load factor of 85% in their calculations of the costs of Gen. III+ reactors (University of Chicago 2004), as does the BNFL in their assessment (British Nuclear Fuel plc & Westinghouse Electric Company LLC 2002) and (Hesketh 2004). The DTI, in its Cost-Benefit analysis of new nuclear build (Kennedy 2007), has assumed a load factor of 80%, rising to 85% after the first 5 years. In the same paper, a summary of other relevant studies shows that averages are between 75-95%, with most studies assuming 85% for their calculations. Based on this evidence, an estimate for the capacity factor of 85% was also used in this work.

5.6 *“Back End”*

Although the stages attributed to the “Back End” of the fuel cycle vary, depending on the country and time of study, it is the aim of this study to make the nature of this life-cycle stage as comprehensive as possible. This way it is hoped that the results will reflect the future conditions that might apply by the time the reactor is due to be decommissioned, from 2070 onwards. This study differentiates itself from other studies on the U.K. nuclear fuel cycle, in that it does not cover the aspect of fuel reprocessing. Currently, the U.K. has a policy of reprocessing the spent fuel from domestic and overseas operators, to extract uranium and plutonium and for the manufacture of Mixed Oxide fuel, also known as MOX fuel. For this study however, this aspect of the domestic fuel cycle has been omitted due to the complexity of providing accurate modelling and more importantly due to the fact that it would make it harder for results of the lifecycle to be widely applicable. Also, given the importance of security of nuclear waste, spurred on by concerns of nuclear weapon proliferation and the ever-present shadow of nuclear terrorism, it has been argued that the ‘once-through” cycle is the most appropriate (Massachusetts Institute of Technology 2003). Based on the previous conditions, the stages accounted for in this study, the assumptions made and the available information, are described in the following sections.

5.6.1 Decommissioning

Despite the examples of decommissioning in E.U. countries, almost no empirical data is available on this phase of the life cycle. What little does exists, is based on estimates of the projected economic costs and therefore existing studies that cover the decommissioning phase employ the I/O method, in order to establish energy requirements and the associated emissions. (Storm van Leeuwen 2007) provides a summary of existing studies, but highlights that it is not possible to establish whether some of the studies are using the same reference case as their basis.

As such other approximations were chosen to establish a value for the energy requirements for the decommissioning phase. Based on estimates in the report from the University of Sydney (ISA 2006), a value of 35% of the energy required for construction can be attributed to this stage. However, sources quoted in Ecoinvent literature (Dones R. 2003), assume 75% of the construction energy would be required for the decommissioning of a NPP. This is the value used in this work as this would appear to be a conservative value. A point of note is that commentators expect the decommissioning of the AP1000 (or any Gen III+ design) to be more straight-forward, due to the fact that this stage has been considered during the design of the reactor. As such, the fact that there is a reduced number of components and that the reactor is based on a modular design, should mean that decommissioning requirements should be lower than for current reactors (Sustainable Development Commission 2006d). This would mean that the value used for the energy requirements in this work, is most probably highly conservative.

5.6.1.1 Wastes arising from the operation of the AP1000 reactor

The wastes that should arise from the operation of a nuclear power plant, based on the AP1000, were detailed by BNFL/Westinghouse in their consultation of the AP1000 (British Nuclear Fuel plc & Westinghouse Electric Company LLC 2002) and by NIREX in the U.K., as part of their assessment of new nuclear build (Vande Putte D. & NIREX UK LTD 2004). For this report, the waste estimations are based mainly on the first report mentioned, while it should be noted that there is a high level of agreement between the figures in the two studies. The same values have also been used by the NDA in their submission to the U.K. Government’s Consultation on the future of nuclear power (NDA & Gilchrist 2006). As such, it is calculated that a AP1000 reactor will lead to the creation of 1,400 tHM of Spent Fuel/High Level Waste (SF/HLW), 900 m^3 of Intermediate Level Waste (ILW) and approximately 8000 m^3 Low Level Waste (LLW). All the volumes represent the “packaged” volumes, as will be explained in the following section. It is also assumed that current procedures, which exclude the reprocessing of Sizewell B spent fuel, will also apply to the next generation of PWRs.

5.6.1.2 Relationships between the different waste classifications

Due to the nature of the nuclear fuel cycle and the ambiguity in the classification of the various materials resulting from the operation and decommissioning of a NPP, it was necessary to use approximations when calculating the different waste streams. These different streams varied according to the variations that were made to the original assumptions for which quantities in each waste stream were originally defined. As existing equations in this research permitted only the amount (mass) of spent fuel to be accurately calculated (see Appendix B), it would be impossible to estimate directly the amount of ILW/LLW waste that would arise from changing different operational parameters (e.g. lifetime, burnup etc). In the literature, there appears to be no information on how the volumes of ILW and LLW are calculated. Hence, it is unclear how variations in the basic assumptions (that led to the calculation of the original volumes stated previously), would affect the lifecycle quantities of waste. Also, no detailed information concerning what exactly was included in the original estimates of ILW and LLW was available. The only indication, as to the composition of the waste streams, is provided in (Vande Putte D. & NIREX UK LTD 2004) where the main contributors seem to be structural waste from the power plant. This would seem to imply that other wastes (i.e. contaminated soil, scrap etc) do not play an important role. It has to be noted though, that the values for “packaged” waste used by the CoRWM, match more closely the ‘conditioned’ waste values in the “NIREX” report (with the equivalent NIREX ‘packaged’ volumes being 20% higher). No explanation was found for this discrepancy.

As a result of the above uncertainties, it was decided to assume a direct linear relationship between the mass of the Spent Fuel (which was calculable) and the volumes of ILW and LLW (which were not). The scaling rule was based on the CoRWM's quantity estimates and was described by the following ratios:

$$ILW(m^3) \Big/ Spent\ Fuel(tU) = 0.643 \text{ and } LLW(m^3) \Big/ Spent\ Fuel(tU) = 5.71$$

"Stored", "Conditioned" and "Packaged" volumes

In the UK Radioactive Waste Inventory, two waste states are distinguished: "as stored" and "as conditioned". Conditioning is the term applied to the processes used to prepare the wastes for longer-term storage and/or disposal. Conditioned wastes are packaged in steel containers, usually having been encapsulated in cement or some suitable grout. Wastes that have not yet been finally conditioned may have undergone some form of preliminary treatment for the purpose of storage. Volumes recorded in the Inventory under the "as stored" heading refer to the actual volumes that wastes occupy in store, and include untreated wastes, and those in interim conditioned form (RWMAC & NuSAC 2002). "Packaged" volumes relate to waste that has been placed in the final containers that will be used for permanent storage in a repository. NIREX has undertaken significant work in the design and description of these packaging procedures as can be seen in reports (NIREX UK LTD 2003;NIREX UK LTD 2005a;NIREX UK LTD 2005b;NIREX UK LTD 2005d;NIREX UK LTD 2006), which relate to the Phase Geological Repository Concept.

Once again, due to a lack of detailed data to describe the exact conditioning procedures for nuclear waste, it was necessary to apply scaling rules to the different waste volumes in order to be able to convert between the different packaging volumes. Using the volumes described in (Vande Putte D. & NIREX UK LTD 2004), it was calculated that for ILW, the following ratios apply:

$$\frac{"Packaged"\ volume\ (m^3)}{"Stored"\ volume\ (m^3)} = 3.79 \text{ and } \frac{"Packaged"\ volume(m^3)}{"Conditioned"\ volume(m^3)} = 2.98$$

For LLW, the ratios that apply are:

$$\frac{"Packaged"\ volume(m^3)}{"Stored"\ volume(m^3)} = 1.32 \text{ and } \frac{"Packaged"\ volume(m^3)}{"Conditioned"\ volume(m^3)} = 1.19$$

Finally, for the spent fuel, a conversion was required between the mass of the fuel and its volume, once it was packaged for final disposal. This relationship was already provided by the CoRWM, who assumed that 14,000 tHM would equate to 31,000 m^3 of packaged waste.

The above ratios were required in order to model the different stages of the "Back End", as many modules were based on different "types" of waste volumes.

5.6.2 Interim Storage

The stage of Interim Storage in the model created for this research is designed to be a temporary storage for Low (LLW), Intermediate (ILW) High Level Waste (HLW) and Spent Fuel (SF). Many studies include Spent Fuel and High Level Waste in the same category. This is done mainly when a reprocessing policy applies, since the spent fuel ends up in the form of new fuel while high level wastes result from the conversion. As it is assumed that no HLW will be generated from the operation of a Gen. III+ fuel cycle (i.e. HLW attributable to the AP1000, will be non-existent due the lack of fuel reprocessing or included for all practical purposes in the spent fuel category), the description of that waste stream has been omitted. A description of current U.K. practices and the modelling assumptions for each waste stream is undertaken below.

For the purposes of this study, the different waste streams were modelled separately, according to current or near-term industry practices for interim storage. Very little data on this stage of the “Back End” is publicly available, probably due to the sensitive and controversial nature of this phase in the lifecycle. Even for the information that does exist, it is relatively difficult to separate the different disposal routes (i.e. direct storage from reprocessing), due to the U.K.’s current policy on nuclear waste treatment. These concerns have led to the decision to model this part of the fuel cycle using a theoretical scenario, which however still adheres to real-life practices as much as possible. For this stage, many assumptions were taken and adapted from the Ecoinvent database. The database’s entry is based on a study carried out on a theoretical scenario for the Swiss waste management, and as such is also only an estimation, not a representation of real life procedures.

In this research, it has been assumed that the Spent Fuel and ILW streams are sent to a central storage facility. In the case of the SF, this involves emplacement in flasks (as described above) and storage in a pool, while the ILW is assumed they undergo the process of cementation, in order to immobilise the wastes. This choice in many ways, reflects the real situation, where wastes are taken to Sellafield for storage and processing. However, as it has not been possible to get enough information on for this facility or the treatments that wastes are subjected, it was decided to use generic data (based on the Ecoinvent entry). Low level waste is assumed to be sent to a centralised interim storage facility and were it is treated. The modelling of this stream is follows real life procedures, in that it reflects current practise, where waste is sent to Drigg. The main difference of course is that Drigg is assumed to provide end storage/disposal, not just interim storage.

5.6.2.1 Spent Fuel Interim storage

Based on the data used in by the NDA in their report (NDA & Gilchrist 2006), it is assumed that the AP1000 reactor’s waste will be classified solely as Spent Fuel.

Since very little analytical operational data was available for UK facilities, the conditioning and interim storage of SF in the UK, was modelled based on the Ecoinvent entries edited to better mirror UK conditions. It has been assumed that the spent fuel is placed into flasks for transportation and then taken to a central facility where it is placed in storage ponds. Cooling is achieved through convection. The infrastructure (i.e the requirements for the construction of the facility) is represented by the Ecoinvent entry. For the facility operation, the estimates from the Ecoinvent model were taken and modified accordingly. It was assumed that the facility had ventilation (HVAC) requirements of approximately 1430 kW_e with a loading of 50%, while the active cooling was rated at 520kW_{th}, utilised 20% of the time. The operational lifetime is 55 years. It was also necessary to include the material and energy requirements for the flasks in which the spent fuel would be stored. Detailed descriptions of these flasks were not found, so they were modelled using the final disposal canisters as a rough guideline. Specifically, NIREX in their work for the Depository Concept, discussed the general dimensions of a canister to be used for positioning in the underground repository (NIREX UK LTD 2005b). This has been modified according to the description provided above by (IAEA 2007). A diagram with the general canister dimensions can be seen below:

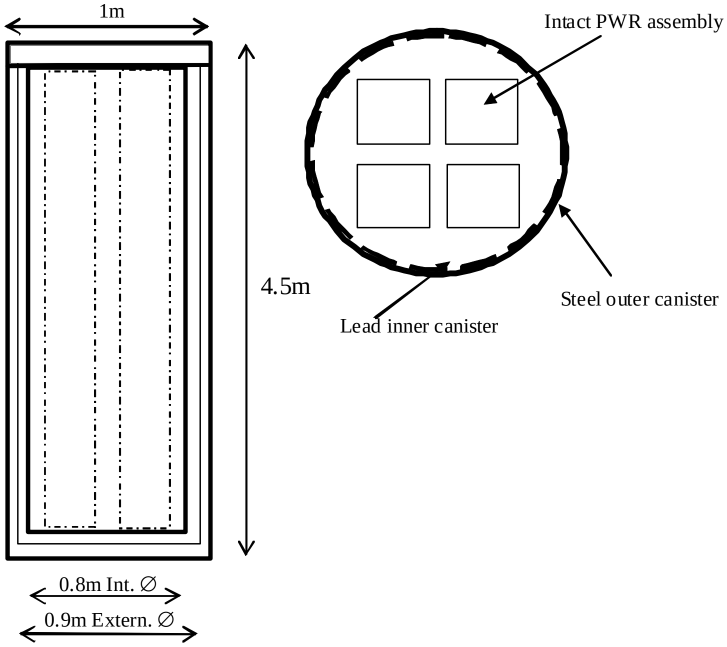


Figure 5.6 Schematic of storage/transportation canister

It assumed that the canister is 4.5 m high and has an outer diameter of 1m. The canister is made of a 0.1m thick outer layer of steel and then an inner sleeve of lead, also 0.1m thick. The canister can take 4 intact PWR assemblies. Using the above dimensions, it was calculated that each canister requires approximately $0.8m^3$ of steel and $0.675m^3$. Based on the calculations in (NIREX UK LTD 2005b), 1,150 tU equate to approximately 2288 fuel bundles which require 572 canisters. This in effect equates to 2 tU per canister. From (Sustainable Development Commission 2006d), it is stated that the AP1000's 14,000tU would have a packaged volume of 20,000 m^3[♦].

Transportation assumed to be by rail over a nominal distance 250 km.

5.6.2.2 Intermediate Level Waste (ILW) modelling

As with all the "Back End" of the UK nuclear fuel cycle, very little data exists to describe the processes. As such this stage was modelled using Ecoinvent data concerning a hypothetical Swiss scenario, modified to better represent potential UK

[♦] The CoRWM calculated different volumes for the packaged spent fuel ($31,900m^3$). NIREX have used canister dimensions from the Swedish KSB-3V concept (Sustainable Development Commission 2006d). Since this work is based on the NIREX concept, those values have been used in this report.

circumstances. It is assumed that the ILW will be immobilised in cement (cementation) and stored in a canister. According to the Radioactive Waste and Materials Inventory (CoRWM 2005), conditioned waste contains between 40%-80% immobilising matrix. For the modelling of the cementation is has therefore been assumed that 60% of the volume of the conditioned waste is evenly split between the added cement and the steel canister containing it. Processes have also been added for welding of canisters, the mixing of cement and the use of electricity for the various equipment, based on the Ecoinvent module for the conditioning of spent fuel. Finally, electricity use for the cooling and ventilation of the waste has been including based on Ecoinvent. The infrastructure factor is based directly on the Swiss model estimates.

5.6.2.3 Low Level Waste (LLW) modelling

Given the storage problems associated at the time of writing with the storage of LLW, it has been assumed that any wastes arising from a new round of nuclear build will require new facilities both for interim storage and final disposal. Due to the lack of data concerning current operations, LLW interim treatment and storage was based on a modified entry in Ecoinvent. Specifically, it was assumed that the LLW would first undergo incineration to reduce its volume (based on the Swiss ZWILAG concept, modelled in Ecoinvent leading to a reduction in volume of 93 times) and then cementation to immobilise the ashes (based on the rules of thumb that $1m^3$ of conditioned LLW containes 0.787 m^3 of “stored” waste”. These assumptions, were combined with the estimate for the immobilising matrix from the ILW, to give a final figure for the conditioned waste for interim storage. The actual facility where the waste is kept is taken directly from Ecoinvent and adapted to UK conditions.

5.6.3 Final Storage for radioactive waste

The modelling of the final repository for U.K waste is based on the work carried out by NIREX. Specifically, the modelling is based on the work detailed in (NIREX UK LTD 2003) and (NIREX UK LTD 2006). The work has also been summarised for use in the British Energy’s EPD for the Torness power station (NIREX UK LTD 2005c). The work is based on the creation of two underground repositories, one for the permanent storage of LLW and ILW, otherwise known as the Phased Geological Repository Concept for ILL/LLW, while the other would be utilised for the final disposal of HLW and spent nuclear fuel, in what is described by NIREX as the Reference HLW/SF Concept.

5.6.3.1 Reference HLW/SF Concept

Conditioning SF

According to NIREX’s original calculations, waste destined from the HLW/SF Repository would be placed in special canisters. The original specifications for the SF/HLW repository as quoted in (NIREX UK LTD 2005b), state that the SF/HLW Repository is designed to contain 7088 canisters of vitrified HLW, and AGR and PWR spent fuel. However the disposal canisters vary for each waste type, as can be seen from the following table (Table 5.10):

	CANISTER LENGTH (m)	CANISTER DIAMETER (m)	VOLUME PER CANISTER (m^3)	NUMBER OF CANISTERS	TOTAL VOLUME PACKAGED (m^3)
Vitrified HLW	3.2	0.9	2.04	3700	7548
PWR Spent Fuel	4.5	0.9	2.86	572	1636
AGR Spent Fuel	2.5	0.9	1.59	2816	4477
			SUM	**7088**	**13661**

Table 5.10 Volumes of waste to be held by the Repository

From the above table it can be seen that the Repository was planned to accommodate approximately 13,661 m^3 of packaged waste (or 7088 canisters). The disposal canister for PWR fuel elements is designed to contain 4 complete elements and would be approximately 2.86 m^3 in volume (4.5m long and 0.9m in diameter). The information provided indicates that the canister will most likely be made of a combination of copper for the actual cylinder with cast iron used for inserts. An estimation of the material requirements for each cylinder can be seen in the following table:

	MASS OF COPPER (tonnes)	MASS OF CAST IRON (tonnes)
1 PWR disposal canister	6	9.2

Table 5.11 Estimated mass of materials for the manufacture of a SF canister

In NIREX's specifications to waste package manufacturers (NIREX UK LTD 2005d), it stated that the welding on the canisters should be kept to a minimum. As such it has been assumed that the materials are either cast or extruded. The energy and transportation requirements for the conditioning of the waste have been borrowed from the equivalent Ecoinvent entry, which itself is based on a slight older design of the same canister.

Scaling of Repository

Its has been assumed that the spent fuel from the AP1000 reactor will not differ substantial from that of the current operating PWR reactor, Sizewell B. Based on the NIREX calculations in (NIREX UK LTD 2005b)four PWR elements would be packaged inside a single disposal canister. From the same report it states 2288 PWR elements contain 1150 tU. From this, it is possible to calculate that a fleet of 10 AP1000 generating 14000 tU over their lifetime would equate to 27,854 PWR elements. Given that 4 PWR elements are contained in 1 SF canister, that would mean that the lifetime spent fuel of the AP1000s would fit in 6,964 SF canisters, taking up approximately 20,000 m^3 (19,917 m^3). This figure agrees with the NIREX estimate as quoted in (CoRWM 2005), but differs from CoRWM's own estimate (31,900 m^3). However, it is understood that the latter estimate is based on different size disposal canister. For the sake of continuity, this report assumes the original NIREX specifications. As stated above, it is calculated that 10 AP1000 reactors would generate 14000 tU, which equates to 20,000 m^3 of packaged waste. The repository is designed to accommodate 13,661 m^3 of packaged waste, meaning that it would need to be scaled up by approximately 49% from the original design to accommodate the new waste. This would mean that the infrastructure factor per m^3 of packaged waste would be 2.99×10^{-5}.

Construction

NIREX's Technical Note for the HLW/SF Repository (NIREX UK LTD 2005b) and its input to the Torness EPD (NIREX UK LTD 2005c) provide information on the basic quantities of material required to build the facility to house the calculated amount of waste. A summary of the unscaled bill of materials can be seen in the table below:

	TOTAL QUANTITY OF MATERIALS FOR HLW/SF CONCEPT	
Bentonite Buffer	434,681	tonnes
Concrete for operating plugs	42,532	m^3
Reinforcement Steel for operating plugs	320	tonnes
Concrete for permanent plugs	18,619	m^3
Reinforcement for permanent plugs[1]	50	tonnes
Decommissioning backfill material[2]	1,228,345	m^3

1. No information is given as to the design of the "permanent" plugs, but in line with the "operational" ones, it is assumed that the material is steel
2. The Backfill Material consists of a mixture of crushed rock (70%) and bentonite (30%)

Table 5.12 Quantities of construction materials for the HLW/SF Repository

The only information provided about the actual construction procedures of the Repository concerns the amount of explosives that would be required (6250 tonnes). In order to compensate for the lack of data, the construction energy requirements per m^2 of building were inputted manually based on existing Ecoinvent processes. From (NIREX UK LTD 2005c), it is stated that the HLW/SF and ILW/LLW facilities would have a surface land take of approximately 1,000,000 m^2. Due to the lack of definition it has been assumed that the area is equally divided between the two facilities. It is also stated that the HLW/SF Repository would have an underground area of 3,000,000 m^2.

Operation

In the information provided in (NIREX UK LTD 2005c), it is stated the Repository would have a constant load of 3 MW. This was scaled up together with the other parameters to accommodate the increase in waste after the AP1000 fleet is decommissioned. The operational life of the repository has been designated in (NIREX UK LTD 2005c) and (Ernst & Young LLP 2006) as between 40-50 years. During this time the waste will be emplaced and actively monitored, but after this 50 year period, the backfilling of the facility will take place until final closure 10 years later. For the purpose of modelling, it has been assumed that the lifetime of the Repository is 50 years.

Transportation of waste

It has been assumed that the packaged containers are moved a nominal distance of 100km by rail and 100km by truck, based on estimations of current transportation distances for nuclear waste.

5.6.3.2 Phased Geological Repository Concept for ILW/LLW (PGRC)

The PGRC covers the final disposal of ILW and LLW that is otherwise unsuitable for disposal at the facility at Drigg. Once waste has been packaged appropriately to NIREX standards and specifications, it is transported to the centralised repository facility were it is emplaced in the purpose-built vaults at depth is suitable geological formations. This would be followed by a period of monitoring which could in theory be extended indefinitely, providing the possibility of retrieving the waste should that be required. Otherwise this stage is followed by the backfilling of access tunnels to the waste and the permanent enclosure of the material.

Scaling the ILW/LLW Repository

In NIREX's submission to the Torness EPD (NIREX UK LTD 2005c), the quantity of materials for the construction of a generic ILW/LLW Repository is outlined. The Repository is sized based on NIREX's variant case, which envisioned the storage of 256,000 m^3 of conditioned waste. This waste would be made up of approximately 226,000 m^3 of ILW and 30,000 m^3 of "non-Driggable" LLW. Updated values from CoRWM give an estimate of 348,000m^3 of packaged ILW and 37,200m^3 of packaged LLW (242,000m^3 conditioned ILW and 31,200m^3 conditioned LLW respectively) Based on these values, the total packaged volume would be in the region of 385,200 m^3. This would mean that a program of 10 AP1000s would generate a combined total of 89,000 m^3 packaged waste, indicating an increase of 23% on the baseline volumes. This can be seen analytically in the following table:

CURRENT BASELINE	ILW	LLW	TOTAL
Conditioned (m^3)	242,000	31,200	
Packaged (m^3)	348,000	37,200	385,200
10 x AP1000			
Packaged (m^3)	9,000	80,000	89,000
Increase (%)	-	-	**23.1**

Table 5.13 Volumes of waste destined for the I/LLW Repository

As such, the information concerning the quantity of materials was scaled up by this factor to accommodate the increase of encapsulated waste. The resulting infrastructure factor was calculated to be 2.11 x 10^{-6}.

Construction

MATERIAL	QUANTITY FOR ILW/LLW REPOSITORY	UNITS
Crushed Rock for general backfill and roadway seals	1,000,000	tonnes
Concrete for permanent plugs	29,772	m^3
Reinforcement for permanent plugs	60	tonnes
Vault backfill materials		
Portland Cement	149,365	tonnes
Hydrated Lime Aggregate	56,427	tonnes
Limestone Flower	164,302	tonnes
Stainless Steel for encapsulation	23,823	tonnes

Table 5.14 Material requirements for the construction of the I/LLW Repository

As with the HLW/SF Repository, the only information concerned with the direct construction energy requirements was the amount of explosives required (3750 tonnes). In order to include the energy requirements of actual construction, the construction energy requirements per m^2 of house were inputted manually based on existing Ecoinvent processes. From (NIREX UK LTD 2005c), it is stated that the reference ILW/LLW Repository will have an underground area of 1,200,000 m^2. As before the surface land-take was taken to be half the 1,000,000 m^2 estimate from (NIREX UK LTD 2005c).

Encapsulation Canisters

Table 5.14 includes data on the amount of stainless steel required to encapsulate the wastes described previously. Because however, no detailed information was available about the packaging of the waste and its material composition (as was available for the Spent Fuel), it has not been possible to model the packaging of the ILW and LLW with any accuracy. As a result, the steel required for encapsulation has just been included in materials for the Repository infrastructure and scaled accordingly.

Operation

In the information provided in (NIREX UK LTD 2005c), it is stated the ILW/LLW Repository would have a constant load of 3MW. This was scaled up together with the other parameters to accommodate the increase in waste after the AP1000 fleet is decommissioned. The Repository is expected to have a land-take of approximately 500,000 m^2 (based on the assumption that the quoted 1,000,000 m^2 is evenly split between the ILW/HLW and HLW/SF facilities). The operational life of the repository has been designated in (NIREX UK LTD 2005c) and (Ernst & Young LLP) as between 40-50 years. During this time the waste will be emplaced and actively monitored, but after this 50 year period, the backfilling of the facility will take place until final closure 10 years later. For the purpose of modelling, it has been assumed that the lifetime of the Repository is 50 years.

5.7 Summary of Nuclear power lifecycle model

As can be seen from the preceding sections, the nuclear lifecycle is comprised of complex stages that need to be accurately modelled in order to provide an accurate approximation of the overall model. In this chapter all the collated data and assumptions used, are highlighted and then combined to provide a thorough basis for the creation of a lifecycle model for computations regarding the nuclear power lifecycle.

6. Wind farm lifecycle modeling

6.1 Introduction

The purpose of this chapter is to outline the basic concepts behind the utilisation of wind power and to illustrate how the wind farm models used in the comparison were created. An analytical exposition of all the inputs into each model is provided, detailing all the assumptions made to facilitate the creation of an accurate lifecycle model of an onshore and offshore wind farms.

Each wind farm model is presented separately in order to adress the main differences in modelling requirements. As such, the two wind farms are modelled using different turbine types (a 1.5 MW turbine onshore, and 3.6 MW and 5 MW turbines offshore), different foundations (and in the case of the offshore wind farm, three different types of offshore foundations) while there are also differences associated with assumed on-site erection and maintenance requirements.

6.2 Onshore Wind Farm model

The wind farm created for this study is based on current and near future trends in wind farm building projects. In order to properly size and build the model, data from a real wind farm were used as a reference and the existing conditions at the real site were modelled as closely as possible with the available data. As the aim of this analysis to undertake the modelling of a wind farm that will meet current and future wind farm development expectations, the first step to creating a model was to establish areas of current and projected future wind farm development. From statistics provided by the British Wind Energy Association (BWEA) (BWEA 2009a) which account for projects that are being built, have building permission and are awaiting consent, the vast majority of current and projected wind farm development onshore (approximately 58% on an installed GW basis), is being undertaken in Scotland. This can be seen as a clear indication that Scotland therefore is the most representative area for wind power development in the British Isles. Further examination of Scotland in particular shows that most developments are concentrated in the lowlands of the country, close to the borders with England. This is not unexpected as, apart from good wind resource, developments are easier there than in the Highlands, while the wind farms are easier to plug into the grid and closer to the sources of demand.

With the geographical area of interest established, the next step to creating a representative model of a wind farm is to choose a project that illustrates the nature of future wind power developments. After careful consideration of wind farms currently in construction, the reference wind farm used for this study was the Whitelee onshore wind farm which was given planning consent in early 2006. Situated on elevated ground in East Renfrewshire, south of Glasgow in Scotland, the wind farm is projected to be comprised of 140 wind turbines with a maximum output of 322 MW (dependent on the size of wind turbine chosen). When completed, the wind farm is expected to be able to provide approximately 2% of the Scottish electricity requirements in a typical year. The site, as envisaged at the time of consent, will be approximately 55 km^2 in size (Scottish Executive 2006).

The output of the wind farm will depend on the size of the wind turbines that are chosen for the installation. However in the Whitelee Wind farm Non-Technical Summary (CRE Energy Limited & ScottishPower 2006), only the maximum dimensions of the wind turbines are set out (70m tower height and 80m blade diameter). The proposed construction will include 76 km of roads and underground power cables, a site substation as well as a Visitor's Centre. The size of the wind farm is, to some extent, determined by the capacity of the grid connection tolerances. The wind farm's operational lifetime is expected to be 25 years, with a 2 year construction period and one year to decommission the site at the end of the electricity generation (CRE Energy Limited & ScottishPower 2006).

The model created for this analysis includes all aspects of the wind farm life cycle, covering construction (both site work and wind turbine assembly), operation and decommissioning at the end of the 25 year operational lifetime. It should be noted that in this research it has been assumed that the turbine installed onsite will have a capacity rating of 1.5 MW. As such, the installed capacity of the site will be 210 MW which is within the maximum limit of 322 MW, but less than the projected wind farm capacity. A summary of the model wind farm characteristics can be seen in the table below:

LOCATION	WHITELEE, EAST RENFRENISHIRE
Rated Output (MW)	210
Number of turbines	140
Turbine Rated Output (MW)	1.5
Project Lifetime (years)	25

Table 6.1 Wind Farm Characteristics

In order to calculate the potential output of a wind turbine it is first necessary to estimate the wind regime at the site of the proposed wind farm. In order to do this, it is necessary to have an understanding of how wind power works and what the requirements are for providing an accurate estimate of energy output. An analytical explanation of how the model was setup, as well as information on all major assumptions, is presented in the following paragraphs.

6.2.1 Site description

An important aspect of any wind resource analysis is the assessment of the terrain surrounding the wind farm. This is necessary because it forms an important input into the wind flow modelling (in the form of elevation and surface roughness changes) as well as an indication of the likely effect that the features of the surrounding terrain (e.g. trees, buildings) will have on the performance of the wind turbines. For the assessment carried out for this research it was not possible to carry out analytical wind flow modelling but the assessment of the terrain still influenced the estimation of wind speed variation with height, as will be seen in following sections.

Using online map services and information provided by the British Wind Energy Association ((BWEA 2009b)), the location for the wind farm was established to be approximately at the coordinates of 55 41 14N by 04 13 43W [1]. This estimate was cross-referenced with the information provided in (CRE Energy Limited &

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[1] UTM system, WGS 84 datum

ScottishPower 2006). A satellite image of the wind farm location can be seen below in Figure 6.1 (Google maps 2009). As can be seen from the image, the area surrounding the wind farm is characterised by extensive forestry. Based on the roughness classes described in Chapter 4 and defined in (Danish Wind Industry Association 2008; Troen and Petersen 1989), these forestry features were assigned a roughness value of 0.4 m. There are also some lake to the north and northwest of the site, which will also influence the behaviour of the wind flow as it approaches the wind farm from those sectors. These accordingly have been assigned values of 0.0002 m.

Figure 6.1 Whitelee wind farm surrounding terrain

Finally, the terrain not immediately associated with forestry was assessed to consist of fens and bogs, with low level vegetation in the form of shrubs and tall grasses. Using the aforementioned classification system, this type of terrain was assigned a value of 0.03 m. The assessment of the terrain type was further assisted by images of the wind farm site, available in the public domain, as can be seen below, in Figure 6.2 (taken from (Brown 2009;Scott 2008)).

Figure 6.2 Images of Whitelee Wind Farm

6.2.2 Wind resource at proposed site

As previously described in Chapter 4, the most important input to an energy production assessment, is a description of the wind resource available at the proposed site. In the case of the Whitelee wind farm, no publicly available site specific information was available in literature sources to help estimate the wind resource for the onshore wind. This led to a search for data recorded at nearby locations which could then be adapted to produce estimates for the wind farm location. The UK Meteorological Office through its network of sensors has an extensive collection of meteorological data for various locations throughout the United Kingdom (known as the MIDAS Land Surface Observation Stations Data). For the exact location of the proposed wind farm (Whitelee, South Glasgow), as already stated, no wind speed data was readily available but several meteorological stations that could provide information were identified. After this meteorological stations had been filtered for distance (i.e. all located within 50 km of the site), 3 options were found to be available. A summary of the stations can be found in the following table:

Met Station	Altitude [m]	Distance [m]	Direction
Prestwick RNAS	27	30	Southwest
Salsburgh	277	30	Northeast
Drumalbin	245	32	East

Table 6.2 Reference stations near the proposed wind farm

The meteorological data from the meteorological stations, as provided by the MIDAS database, contained consistent hourly averages of wind speed and direction for the period November 2001 until present for the Prestwick station, January 2000 until present for Salsburgh and June 1991 until present for Drumalbin. In the MIDAS user guide (United Kingdom Meteorological Office 2008), it is stated that for all meteorological stations measurements “the standard exposure is over level, open terrain at a height of 10m above the ground”. Using this data, the average mean wind speed at 10 m was established and can be seen below:

Met Station	Average Mean Wind Speed [m/s]
Prestwick RNAS	4.7
Salsburgh	6.0
Drumalbin	5.8

Table 6.3 Wind speeds at reference stations

As can be seen from the results above, there is a substantial difference in the wind speeds measured 35 km from the site.

In order to calculate the site wind resource, the preferred method of assessment would be to correlate the data from the chosen meteorological station with any data recorded directly at the site. As it is obvious that the meteorological station will have recorded data for a substantially longer period than what would be available from the site, the correlation would be based on the concurrent period of data between the two locations. Once this correlation had been established, it could then be used to derive a long-term data set for the site by scaling the non-concurrent data by a factor estimated from the concurrent period. This whole scaled data set could be used for the analysis.

However, as no on-site data was available, a standard correlation between the site data and reference station was not a possibility. In order to overcome this shortcoming, a method of scaling wind speeds from the meteorological measurement station was devised, using the relative wind speeds of the site and meteorological station location, as calculated from a third source of information. This third source of information comes in the form of the NOABL wind speed database, as provided by the BERR (BERR 2009). As stated in Chapter 4, the NOABL database provides an indicative measure of the average yearly wind speed at any location in the U.K. and therefore could be used in this case to estimate the relative wind speeds for the two different locations. Using this information, it would then be possible to ascertain the measure of the proposed wind farm site's "windiness" compared to that at the location of the meteorological station.

Using the wind speeds predicted by the NOABL model for the mast locations and the proposed site of the wind farm at 10 m, it was possible to calculate an adjustment factor that would need to be applied to the actual site measured data in order to scale it to a predicted site wind speed. The table below shows the adjustment factor calculated and the resulting onsite wind speed, based on each initiation mast:

Station	NOABL prediction at masts [m/s]	NOABL prediction at site [m/s]	Adjustment factor	Measured wind speed at masts [m/s]	Predicted site wind speed [m/s]
Prestwick RNAS	5.3	7.7	1.48	4.7	7.0
Salsburgh	7.3		1.05	6.0	6.3
Drumalbin	5.3		1.45	5.8	8.4

Table 6.4 Resulting site wind speed predictions using reference station data

Given the range of predicted site wind speeds as seen in the above results, it was decided that a weighted average of three values would provide the most robust solution. As such, the above estimated site wind speeds were weighted using an 'inverse-squared distance' method (based on Shepard 1968), using the following equation:

$$V_{site}=\sum\left(V_1\times\frac{{D_1}/{D_T}}{L}+V_2\times\frac{{D_2}/{D_T}}{L}+V_3\times\frac{{D_3}/{D_T}}{L}\right)\quad(6.1)$$

where

$$V_{1-3}=reference\ windspeeds$$

$$D_{1-3}=\sqrt{\left((x_{site}-x_1)^2+(y_{site}-y_1\right)^2}$$

$$D_T=\sum\left(D_1+D_2+D_3\right)$$

$$L=\sum\left(\frac{D_1}{D_T}+\frac{D_2}{D_T}+\frac{D_3}{D_T}\right)$$

This approach resulted in a predicted site wind speed of 7.2 m/s at 10 m.

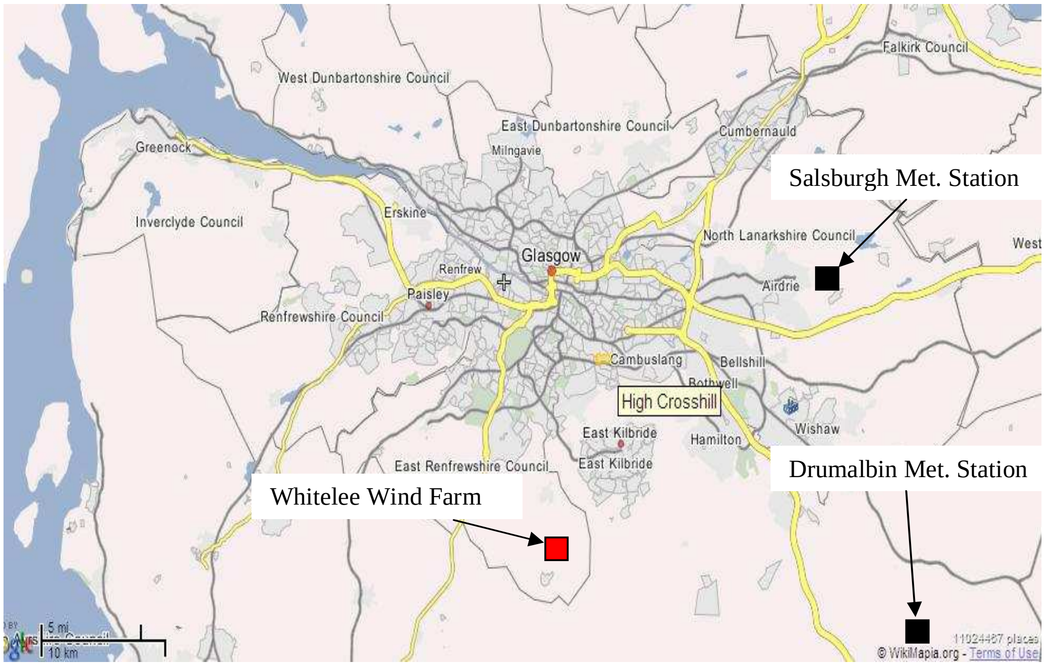

Figure 6.3 Map showing the location of the reference stations and Whitelee Wind farm

An inherent drawback of this methodology is the fact that it is assumed that all of the site is seeing the same wind speeds, i.e. all the wind turbines are experiencing the same wind regime. In reality, this is unlikely to happen and in cases where the turbines are sited in complex terrain, this assumption inherently can introduce large errors in the energy output calculations. This problem is mitigated to some extent through the use of wind flow modeling. For this project however, the use of such techniques was not feasible due to the lack of the appropriate modelling capabilities, but it is believed that due to the relative flatness of the site, the error is within a couple of percent and therefore will be accounted for in the parametric analysis on the site average wind speed.

6.2.3 Calculation of Hub Height wind speeds

As stated in Section 6.2.2, the average annual wind speed as well as the scaled equivalent frequency distribution, were estimated from data recorded at 10 m above ground. However, in order to calculate the wind turbines' energy production, an estimate of the wind speed at turbine hub height would be required. To calculate this value, the equations described in Section 4.3.4 were employed. Specifically, it was decided to utilise the Power Law (Eq. 4.12), but using the simplifying assumptions as provided by (Gipe 2004). This decision was made because these equations provided a conservative estimate of the hub height wind speed, but also because of the lack of accurate data that would be required for utilising the Log Law.

In order to use the simplified equation for the calculation of the shear exponent α, an estimate of the all-directional average roughness value was required. This value was based on an empirical method of estimation, using an image of site extending 10 km in all directions around the wind farm site and the guidelines set out in (Troen & Petersen 1989). Using this image, the percentage makeup of the terrain was then established and weighted by the appropriate roughness classes.

By splitting the area around the wind farm site into 8 sectors (of 45 degrees each), the mix of woodland and grassland was estimated. It was estimated that 75% of the sectors, from the northeast to the west, are covered by a large percentage of woodland (70%) and small percentages of grassland and agricultural land (30%). For the remaining 25%, of the surrounding area, mainly to the north of the site, grassland/agricultural land makes up the larger percentage (estimated at 80%) while woodland less so (20%). Once the estimates were calculated, they were multiplied with values established in Chapter 4, using the roughness classes.

With the all directional roughness value established, the shear exponent was estimated using the simplified expression, as provided by (Gipe 2004):

$$\alpha = \frac{1}{\ln\left(z / z_0 \right)} \quad (6.2)$$

where z is the reference height, i.e. the hub height of the turbines and z_0 is the estimated roughness value. As is implied in the above equation, the wind shear is heavily influenced by the roughness and terrain near the point of measurement. However, it must be noted that the wind flow at any location is affected by terrain many metres upwind of it (Troen and Petersen 1989)

The shear exponent was thus calculated to be 0.18. Given that flat terrain is expected to have a value around 0.14 (Gipe 2004), the value calculated for the wind farm location is not unreasonable, especially considering the dense forest around the area. Indicatively, using this shear exponent combined with the Power Law, the average hub height wind speed was calculated to be approximately 10 m/s.

6.2.4 Onshore Wind Turbine Information

As indicated in previous sections, the wind farm model in this research is based on a generic 1.5 MW wind turbine, as this was the only turbine for which a complete dataset was available at the time of writing. The nominal power output of the turbine assumed in this research is actually lower than that of the actual turbine types chosen for the reference wind farm but the 1.5 MW turbine size is still currently available by most large manufacturers (e.g. Enercon, General Electric and Vestas) and continues to be utilised for projects worldwide. It is important to note that the choice of type and size of wind turbine is dictated by both economic as well as site-specific criteria. Short of a full site analysis however, it is not possible to accurately decide upon the turbine design. As such, it is assumed that the Enercon E-66 used in this modeling is an acceptable choice for the site. It is noted that in late 2006, it was announced that a Siemens 2.3 MW turbine design was selected for the site. A technical summary of the Enercon E-66 1.5MW can be seen in the following table (Enercon Hellas 2007), (Chataignere & Le Boulch 2003). It must be noted that where there was insufficient data for the 1.5 MW model, data was taken from the 1.8 MW version of the turbine, since they share similar technical characteristics.

MODEL:	**ENERCON E-66**
Rated capacity:	1.500 kW
Rotor diameter:	70 m
Hub height:	65 m
Swept area	3421 m^2
Converter concept:	gearless, variable speed, variable blade pitch
Rotor with pitch control	upwind rotor with active pitch control
Number of blades:	3
Rotor speed:	variable, 10 - 22 rpm
Tip speed:	35 – 76 m/s
Pitch control:	three synchronized blade pitch systems with emergency supply
Generator:	direct-driven ENERCON synchronous ring generator
Grid feeding:	ENERCON inverter
Braking system:	3 independent pitch control systems with emergency supply

Table 6.5 E-66 technical characteristics

6.2.5 Energy production

To obtain the energy output of the wind turbine placed in the wind regime as calculated for the site, the approach used was to combine the equivalent frequency distribution with the wind turbine power curve, calculating therefore the energy output at each windspeed interval. The sum of these hourly energy outputs would then provide the energy output from the wind turbine for that year. As turbine power curves are supplied by the manufacturer for non-site specific conditions (usually for an air density of 1.225 kg/m^3 at a sea level), it was also necessary to apply a correction for the altitude and temperature difference between the power curve site condition and the site elevation, using standard equations provided (Gipe 2004).

The power curve utilised in this research is created as a consensus power curve combining the individual power curves of three 1.5 MW machines, the Nordex S70/1500, the NEG/MICON 1500 and the Vestas V63, as provided by (Danish Wind Industry Association 2008) and (Riso Institute 2009). Although obviously the consensus power curve is not specific to any machine, given the difference between the power curves available, it was taken to represent the generic energy output of a 1.5 MW machine.

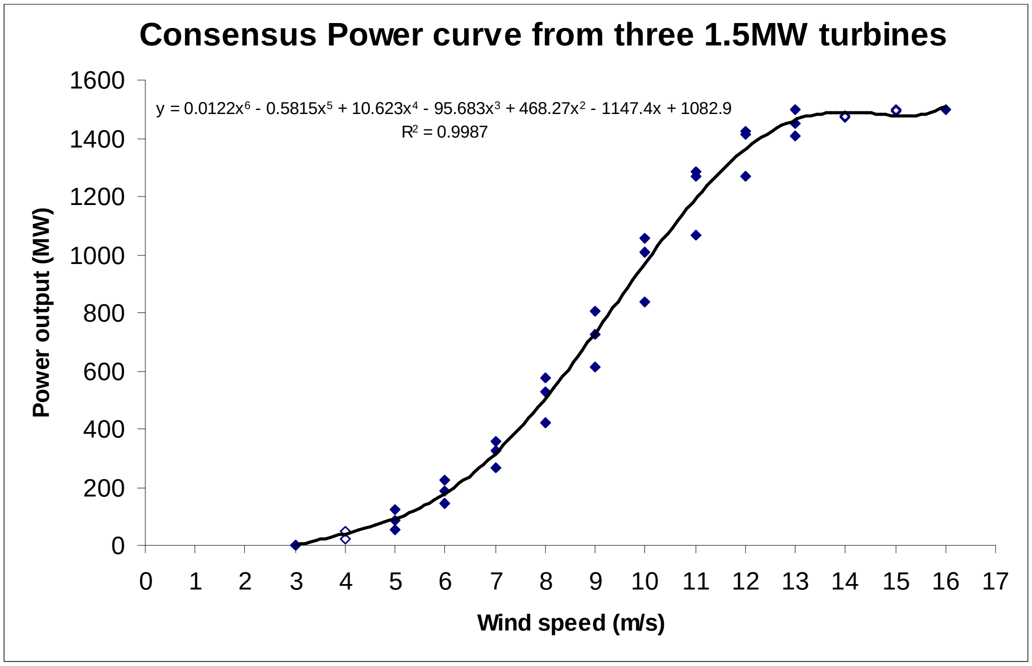

Figure 6.4 Combined consensus power curve for a generic 1.5MW turbine

As can be seen from the graph above, the power curve between 3 m/s and 13 m/s increases and then levels out at the turbine's nominal power until the cut-out speed at 25 m/s. In order to convert it the power curve to a useable format, the power curve was then approximated using the following 6th order polynomial equation:

$$y = 0.0122x^6 - 0.5815x^5 + 10.623x^4 - 95.683x^3 + 468.27x^2 - 1147.4x + 1082.9$$

Thus, with power curve described mathematically, the calculation of the gross energy output of each turbine becomes a matter of multiplying the frequency distribution with the power curve. The total energy of the wind farm then can be estimated as the aggregated energy of all the wind turbines in the wind farm.

Once this energy output has been estimated, downward adjustments need to be made to account for the losses inherent in the operation of any power station, included those specific to wind farms. These losses as described in the following section.

6.2.6 Wind farm energy losses

Six main sources of energy loss are considered in the table below; wake effect, availability, electrical efficiency, turbine performance, environmental and curtailments, each of which is subdivided into more detailed loss factors. These have been explained analytically in Chapter 4 so only a summary of the values applied to this study are given here. A table summarising the energy losses assumed for this project is given below:

Production Losses:	
Wake effect	
Wake effect internal	95.0%
Availability	
Turbine availability	98.0%
Balance of Plant availability	99.8%
Grid availability	100.0%
Electrical efficiency	
Operational electrical efficiency	97.0%
Wind farm consumption	98.0%
Turbine Performance	
High wind speed hysteresis	99.9%
Site specific power curve adjustment	100.0%
Environmental	
Performance degradation – non icing	100.0%
Performance degradation – icing	99.0%
Icing shutdown	99.8%
Temperature shutdown	100.0%
Site access	100.0%
Tree growth (year 1 status assumed)	100.0%
Curtailments	
Wind sector management	100.0%
Grid curtailment	100.0%
Noise and visual	100.0%
TOTAL	87.2%

Table 6.6 Assumed losses for the modelled wind farm

Specifically, the values used above are based on the following assumptions:

1. Wake effect losses

The wake losses of 5% have been assumed based on figures from the Danish Wind Energy Association

2. Availability losses

Over the lifetime of the project, wind turbines, the "balance of plant" infrastructure, and the electrical grid will not be available the whole time. As such a factor needs to be included to account for the losses incurred when one or all of the above inhibits the production and delivery of electricity.

2a. Turbine availability

Availability is an indication of the proportion of time that the turbine is available to produce power and includes the periods when the turbine is on stand-by because of low or very high winds (DTI & DTI Sustainable Energy Programmes 2001). The average wind turbine availability in northern Europe has been calculated to be approximately 98% (Danish Wind Industry Association 2008). Data for the reference turbine model was only available for 2 years but the value presented there matched expectations based on this reference. As such, the availability of the E-66 wind turbine was estimated to be 98% based on the average for the years 2001-2002

(Enercon Gmbh 2003). A monthly breakdown of availability for the E-66 model is shown in the table below:

	E-66 1500 kW	
% availability	2001	2002
January	98.12	97.85
February	98.4	98.1
March	98.55	98.42
April	98.53	98.41
May	98.26	98.34
June	98.38	97.81
July	97.97	97.55
August	97.85	97.43
September	98.21	97.6
October	98.42	96.57
November	98.1	97.09
December	98.16	98.27

Table 6.7 Enercon E-66 turbine availability 2001-2

2b. Balance of Plant availability

This loss factor defines the expected availability of the turbine transformers, the on-site electrical infrastructure and the substation infrastructure up to the point of connection to the grid of the wind farm. The factor assumed here is a standard value taken from (Germanischer Lloyd & Garrad Hassan 1995).

2c. Grid availability

This loss factor defines the expected grid availability for the wind farm. It also accounts for delays in the wind farm coming back to full operation following a grid outage.

3. Electrical transmission efficiency

There will be electrical losses experienced between the low voltage terminals of each of the wind turbines and the wind farm Point of Connection, which is usually located within a wind farm switching station.

3a Operational electrical efficiency

This factor defines the electrical losses experienced when the wind farm is operational and will manifest themselves as a reduction in the energy measured by an export meter.

3b Wind farm consumption

This factor defines the electrical efficiency due to the electrical consumption of the non-operational wind farm due to transformer no-load losses and consumption by electrical equipment within the turbines and substation. More information is provided in Section 6.2.6.1

4. Turbine performance

In an energy production calculation, a power curve usually supplied by the turbine manufacturer is used within the analysis.

4a Generic power curve adjustment

It is usual for the supplied power curve to represent accurately the power curve which would be achieved by a wind turbine on a simple terrain test site. However, for certain turbine models there may be reason to expect that the supplied power curve does not accurately represent the power curve which would be achieved. In such a situation a power curve adjustment is applied.

4b High wind hysteresis

Most wind turbines will shut down when the wind speed exceeds a certain limit. High wind speed shut down events can cause significant fatigue loading. Therefore to prevent repeated start up and shut down of the turbine when winds are close to the shut down threshold, hysteresis is commonly introduced into the turbine control algorithm. As such, this factor accounts for the delay is the restarting of the wind turbine after shutdown and the subsequent loss of power generation.

4c Site specific power curve adjustment

Wind turbine power curves are usually based on power curve measurements which are made on simple terrain test sites. Where it is considered that the parameters in some areas of a proposed wind farm site differ substantially from those at the test site, then the impact on energy production is estimated.

5. Environmental

In certain conditions, dirt and ice can form on the wind turbine blades or over time the surface of the blade may degrade. These influences can impact the energy production of a wind farm as described in 5a, 5b and 5c below. Extremes of weather can also impact the energy production as can be seen in 5d and 5e. Finally, tree growth and felling may impact the production of a wind farm in a time varying manner.

5a Performance degradation – non icing

The performance of wind turbines can be affected by blade degradation which includes the accretion of dirt and other matter which reduce the aerodynamic efficiency of the blades.

5b Performance degradation - icing

Small amounts of icing on the turbine blades can change the aerodynamic performance of the machine resulting in loss of energy. This factor is based on assumptions used by (Germanischer Lloyd & Garrad Hassan 1995).

5c Icing shutdown

As ice accretion gets more severe wind turbines will shutdown or will not start. Icing can also affect the anemometer and wind vane on the turbine nacelle which are used to govern the turbine's operations. These instrument malfunctions can also cause the turbine to shut down. Once again this factor is based on assumptions used by (Germanischer Lloyd & Garrad Hassan 1995).

5d Temperature shutdown

Turbines are designed to operate over a specific temperature range. When temperature at a site exceeds these values then the turbine will be shutdown.

5e Site access

Severe environmental conditions can influence access to more remote sites which can impact availability. As such, a factor is included to account for this downtime due to environmental conditions.

5f Tree growth / felling

For wind farm sites located within or close to forestry, the impact of how the trees may change over time and the effect that this will have on the wind flow over the site must be considered. This is normally done through the use of tree maps that indicate the existing height and location of tree groups and detailed planning of future growth and potential tree felling. However, as this would only be done as part of a full Environmental Impact Assessment, this was deemed beyond the scope of this work.

6. Curtailments

Some or all of the turbines within a wind farm may need to be shut down to mitigate issues associated with turbine loading, export to the grid or certain planning conditions.

6a Wind sector management

Turbine loading is influenced by the wake effects from nearby machines. For some wind farms with particularly close machine spacings it may be necessary to shut down certain turbines for certain wind conditions. This is referred to as wind sector management and will generally result in a reduction in the energy production of the wind farm.

6b Grid curtailment

Within certain grid connection agreements it may be necessary to curtail the output of the wind farm at certain times. This will result in a loss of energy production.

6c Noise, visual and environmental curtailment

In certain jurisdictions there may be requirements to shut down turbines during specific meteorological conditions to meet defined noise emission, shadow flicker criteria at nearby dwellings, or environmental conditions due to such aspects as birds or bats.

Using the above assumptions, and the analytical wind data, the average gross annual energy output (i.e. assuming no altitude or temperature corrections to the manufacturer's power curve) of each turbine was calculated to be approximately 6.58 GWh/yr.

With the estimated yearly output for each turbine calculated, the value was then multiplied by the number of turbines in the wind farm to produce the annual wind farm output. This estimate for the yearly output was finally modified a final time to take into account the losses due to criteria as described in Table 6.6, and calculated to be approximately 13 %. Based on these assumptions, it was estimated that the yearly energy output from the modelled wind farm was approximately 826 GWh/yr, with an average wind farm capacity factor of 42.5%.

The energy yield was also estimated use two other techniques; one based on using the Weibull Distribution and the mean wind speed from the U.K. Met. Office data, and one using the mean wind speed based on the NOABL database. For the Weibull distribution, a *k factor* of 2 was chosen (a fairly consistent value over northern Europe (Gipe 2004)), and the *shape factor C* was based on the equation C = average wind speed at hub height / 0.9, as stated in (Patel 1999). Using the average wind speed from the measured site specific data, the difference in energy yield that was calculated with this method, was found to be less than 2% higher. When the average wind speed from the NOABL windspeed database was used, the divergence was more significant resulting in a difference of almost 13% (the value based on NOABL was higher).

Reverting once again to the values calculated using the analytical wind speeds, it was estimated that the capacity factor for the wind farm, was in the region of 42%. As will be seen from the following section, this value is in line with the predicted capacity factors for that region (southern Scotland), and the U.K. in general.

6.2.6.1 Passive wind turbine energy consumption

A subject that has not received much attention in assessments of wind turbines to date, is that of the passive energy requirements of wind turbines when they are not generating electricity. This phase usually occurs during times of high wind or no wind. Very little data about this topic was found and most of the information gathered was based on educated guesses. It is commonly accepted that wind turbines must consume some energy during "standby", due to the need for power to run equipment in the wind turbine and on the site itself. Possible sources of electricity load are the following:

1. Yaw mechanism - Even when the blades are not turning, the wind turbine is kept in facing in the right wind direction, so that it is in a position to start operating when wind speeds are within its speed envelope.
2. Rotating the turbine but using the generator as a driver – In the event that the wind speed is varying close to the cut-in wind speed, the blades are kept turning using the generator as a driver. This occurs because the wind turbine can start producing electricity easier than from a "cold start" i.e from complete standstill.
3. Lights, communication and monitoring equipment– the wind turbine contains a variety of monitoring and signaling equipment which are always on, irrespective of whether the wind turbine is producing electricity of its own.
4. Heating the blades – When climatic conditions require it, it is necessary to heat the blades to prevent damage from ice build-up. It is quoted unofficially that this heating process might take up to 2-3% of the annual total energy production and be up to 10-20% of nominal power of the turbine. However, it is estimated that as ice build up usually occurs during windy weather conditions, the turbine is seldom consuming energy from the grid (Yes2Wind 2004).

Once again, however it needs to be stated that there are no official sources to back any estimates of electricity consumption up, and so any claims should not be considered valid without further investigation. Generally, it is stated in (Yes2Wind 2004) that when wind turbines are not producing electricity, they consume around 1-2% of their nominal power from the grid. For the purposes of this study, it has been assumed the "parasitic" electricity consumption of a wind turbine is small enough to be ignored.

6.2.6.2 Capacity factors in the U.K.

Another way of stating the annual energy output from a wind turbine is to look at the capacity factor for the turbine in its particular location. The capacity factor depends on many parameters, but mainly on the local wind resource, which in turn depends on the location of the wind farm. As such, there is significant variation in the capacity factor from region to region and from country to country.

For wind farms built from the mid-nineties onwards in the United Kingdom, both Proops (Proops, Gay, Speck, & Schroder 1996) and the ExternE report on Wind and Hydro (CEC, EEE, UK, & ENCO 1995), as summarised by Lenzen (Lenzen & Munksgaard 2002), give a capacity factor for onshore wind farms of 30%. Data on wind farm capacity factors is also provided in the Digest of U.K. Energy Statistics (DUKES) In the 2006 version of the U.K. Digest a new term was introduced to describe the amount of electricity generated from wind farms compared with the amount that such turbines would have generated had they been available for the whole of the calendar year and running continually and at maximum output throughout the calendar year. This term is “load factor on an unchanged configuration basis”. (DTI 2007a). Using the data presented in 2010 version of the Digest (DECC 2010), onshore wind farms where found to have a capacity factor of 26.9% while the offshore capacity factor was calculated to be 33.7%.

In a special feature on renewable energy in (DTI & DT 2006), there is a regional breakdown of capacity factors. Based on this information, the northwest of England has an average capacity factor of 27% for the period 1998-2004. The report also claims that is a direct correlation between indexed UK average wind speed and capacity factors. In the report, ‘Wind power and the UK wind resource’ (Sinden & Environmental Change Institute 2005), the author highlights that the UK has a higher capacity factor (long term average over 27%) than either Denmark (appr. 20%) or Germany (appr. 15%). The report states that this capacity factor is expected to rise as more high wind sites get exploited as well as due to the commissioning of offshore wind farms. It also stresses the need for distribution of wind farms in order to achieve a ‘smoothing out’ of individual wind farm variability.

A different report, published by (Renewable Energy Foundation & Oswald Consultancy Ltd 2006), claimed a UK average based on OFGEM data of 28.2% for 2005. It also went on to refute the claim that widely distributing wind farms helps smooth out their output. Using data for the month of January for a 12 year period, the study demonstrated that large variations in power output were still evident, despite regional distribution of wind generating capacity. As a result, it argues that wind farms deliver energy in short intense bursts which require other plants to cycle up and down to compensate for the variability. This in effect reduced the availability of balancing thermal plants as well as reducing the opportunities for other renewables to generate.

Significantly more specific data has been compiled by the Renewable Energy Foundation (Renewable Energy Foundation & Oswald Consultancy Ltd. 2006), in cooperation with Oswald Consultancy Ltd (the authors of the previously mentioned report). The report compiled by them contains information and about individual wind farms, based on the information provided by OFGEM (as part of the reporting for the ROCs). For the area of the Thames Estuary, the most relevant wind farm was deemed to be that of Kentish Flats, which started operation in August 2005. Due to the lack of data, a capacity factor for only two months (Dec-Jan. 2006) was established, calculated roughly to be 32.6%. The lower capacity factors for the previous months leading up to this period are assumed to be due to the fact that the wind farm was not fully commissioned. Of the wind farms located in southern Scotland, several were used as an indication of the capacity factors of the area. Black Law wind farm project averaged over July 2005- Jan. 2006 a capacity factor of 23.9%. Hagshaw Hill demonstrated an average for 2005 of 29.45% while Hare Hill wind farm demonstrated the highest capacity factor by a significant factor, averaging 44.02% (2005) for Ayrshire. Myres hill wind test site, had a 12 month capacity factor of 28.8%, however, this is based on an incomplete data set (7 months of data).

In what appears to be an update of the original 2006 Oswald Consultancy Ltd report, the Renewable Energy Foundation provided a regional wind energy analysis (Renewable Energy Foundation & Oswald Consultancy Ltd. 2007). The UK wind farms were grouped into ten regions and their performance was summarised. For southern Scotland, the average capacity factor for 2006 was estimated to be 27.6%. The study also summarised the overall capacity factor for offshore wind farms in the UK, giving an average of 29.3%. However, for Kentish Flats which is the most relevant wind farm to the one modelled in the current work, the capacity factor was calculated at 28.8%. The UK average was given at 27.1%. The report also showed that in the areas in question, the capacity factors of 2005 were higher than those of 2006.

As can be seen from the above studies, actual wind farm capacity factors are lower than the estimates provided in more generic reports. It is also interesting to note than in the DUKES figures, although offshore wind originally had a marginally lower capacity factor than onshore, the most recent figures suggest that capacities factors offshore will exceed onshore equivalents, despite the most challenging operating environment. However, there is not enough data yet available from offshore wind farms to be able to draw any types of conclusions.

6.2.7 Onshore Wind Farm Construction

This section deals with the material and energetic inputs required to create the onshore wind farm model. These inputs are based on information gathered from external sources as well as databases as outlined in the Chapter 3. Each stage of the lifecycle is broken down into its modelled components while the information sources and any assumptions made are detailed.

The “wind farm construction” module comprises of two inputs: the “wind turbine” sub-assembly and the “site work” sub assembly. Specifically, the “wind turbine” sub-assembly is multiplied by a factor of 140, which is the number of wind turbines that make up the wind farm, while the “site work” sub-assembly is a single input covering the work and transportation of components required for the construction of the farm.

6.2.7.1 1.5 MW wind turbine data sources

The wind turbine used in this research, as mentioned previously, is based on a 1.5 MW turbine. The turbine model is based on the Enercon E-66. The E-66 is a three-blade horizontal axis wind turbine. This model was in production in the mid- 1990s, until it was superseded by a larger version (1.8MW). Although the design is maybe not completely representative of the latest wind turbine designs, it was chosen for the modelling of the wind farm since it was the most well documented design with an analytical break-down of materials available at the time of writing. It also conformed to the acceptable wind turbine dimensions as specified in the Whitelee Windfarm Non-Technical Summary. The data for the turbine is sourced from a study conducted by the French utility EdF (Chataignere & Le Boulch 2003). The same data, with slight modifications, was also available from a Masters dissertation (Geuder 2004), published on the German WindEnergy Association (BWE) website (BWE 2007). Both these sources have been used in this study to provide a complete dataset for the E-66.

6.2.7.2 Wind Turbine Construction

The wind turbine was modelled by dividing it into the following components, as depicted in Figure 6.4 below:

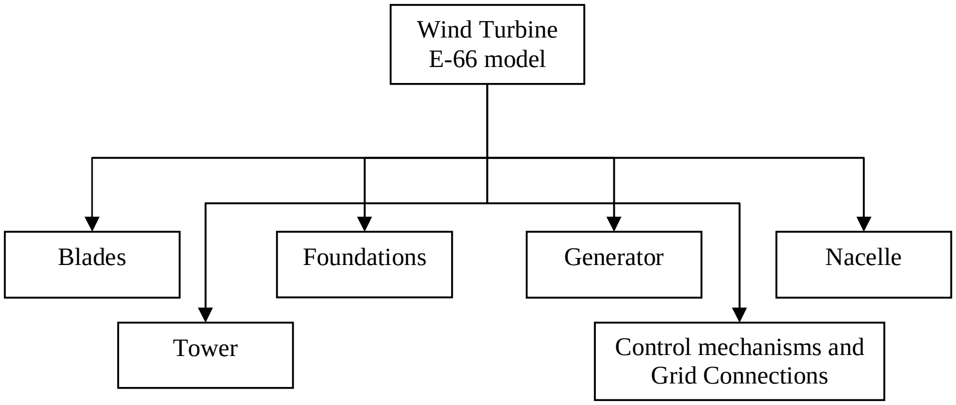

Figure 6.4 Wind Turbine component breakdown

An analytical listing of the construction materials attributed to the E-66 design is given in Appendix C. It must be noted, that although the list of materials used in the construction of the E-66 was extensive, it was not exhaustive. As a result, certain assumptions had to be made and are listed in the following sections.

<u>Blades</u>

The blades, including the nose cone, are the main rotation components of the device. The main materials that make up these components are fibreglass, epoxy resin as well as different plastics (PVC, PE) and cast iron. From the original data set covering the material inputs to this construction module, all but two materials were accounted for in the databases used in this research. Specifically, a certain material was designated as “hardener”, while a further quantity of material was not given a specific description. As it has not been possible to find more information about these two material inputs, the hardener was omitted from the mass balance for the blades. Given that it accounted for approximately 3% of the blade total material inputs by mass, this was judged an acceptable omission which would not bias the total results. This of course is needs to be presented with the caveat that is is assumed that no single material in the wind turbine breakdown can account, on its own, for a large percentage of the energy and emission impacts of the modelled unit. The entry designated as “Other” was replaced by iron, based on the assumption that it represented the material requirements for structural components such as the bolts, supports, brackets etc. A comparison of the blade materials with other reports (Vestas Wind Systems A/S 2005;Vestas Wind Systems A/S & Elsam Engineering A/S 2004) also seems to support this hypothesis.

Nacelle

The nacelle is the housing for the electrical generator and the control mechanisms that regulate the blade angles, rotation speeds and directional controls. It is also the point of connection for the blades and nose cone. The nacelle of this wind turbine model is made primarily of iron and various forms of steel compounds. It also contains amounts of copper and aluminium as well as resins. It should be noted that the generator has been modelled separately, and therefore despite the fact that (Chataignere & Le Boulch 2003) aggregates the materials, the other data source (Geuder 2004) contains a detailed breakdown, which was used instead for this component.

Tower

The tower supports the main unit of the nacelle, which includes the generator, the blades and most of the main control mechanisms. It is made mainly of steel and takes the form of a tapered tube. As stated in Table 6.5, the tower is estimated to be 65 m (to standard hub height). Once again, all energy inputs related to the manufacturing of the tower materials are covered in a separate input, added to the life cycle. The tower is composed mainly of structural steel and iron, and constitutes the largest user of these two materials.

Generator

The generator is the component that translates the blades rotational motion into electricity generation. The main materials that comprise the generator are copper and steel in various forms.

The generator's material inventory also presented difficulties, as certain materials defined in the report by (Geuder 2004), did not contain any supporting explanation or supplementary description. To approximate these materials, the most appropriate material in the databases used was chosen instead for the modeling. Once again where materials were left undefined in the original material breakdown, these were omitted from the model. This was undertaken as it was determined that they only accounted for 1.2% of the generator's mass, and hence it was deemed that there impact on the end results would be minimal.

Grid connection and control mechanisms

This component grouping covered both the control mechanisms contained in the nacelle and the base of the wind turbine, the units required to connect the wind turbine to the local substation, and those required to transmit the electricity to the grid. The control mechanisms are used to alter the blades according to the prevalent wind conditions as well as orientate the nacelle for maximum efficiency. Due to the "dual" nature of this model component, it comprised of large quantities of steel and iron, various plastics and polymers as well as construction materials such as light concrete.

Once again, there was insufficient information about the distinction between certain electrical and electronic components. As such a distinction was not clear in the databases of the life-cycle modelling software used to model this group, a more generic entry from the databases was used that covered a range of electrical components.

Foundations

The foundations, as the name implies, provide the base for the tower unit. They are made primarily from a combination of reinforced (construction) steel and concrete. All the data matched up quite well with original material inventory, so no assumptions were required for this component.

6.2.7.3 Energy requirements for manufacturing, assembly and dismantling

The data for the energy requirements for manufacturing, assembly and dismantling of the wind turbine were taken from the ECLIPSE report (Chataignere & Le Boulch 2003), where it was specified that the total primary energy requirement was calculated to be 379,734 MJ, which based on a even split between electricity and gas gives electricity requirements of 26.3 MWh (0.0945 PJ_e) and natural gas inputs of 2,625 m^3. It has been assumed that, at the end of the turbine's life when it is scrapped, that process requires the same energy inputs.

6.2.7.4 Site Work

The "site work" module covers the work and transportation material and energy requirements for setting up the wind farm. As little data was available for this stage of the life cycle, assumptions and estimations had to be made based on the scarce data acquired. The required inputs can be divided into two categories: the inputs related to the actual site construction work needed to make the farm operational and the inputs that are related to the transportation of the components from the manufacturing facilities to the site.

6.2.7.5 Onsite energy requirements

Once at the site, the wind farm requires the use of heavy machinery to construct the site. For this study it has been assumed that the main contributions in the site construction are from hydraulic diggers (for the preparation of the wind turbine foundations) and from cranes used to erect the turbines. For each turbine, the foundations required the removal of approximately 450m^3 of earth, based on the data provided by (Vestas Wind Systems A/S & Elsam Engineering A/S 2004). (Rydh, Jonsson, & Lindahl 2004) reports that it is assumed that the installation of a wind turbine requires approximately 16 hours worth of crane work. The on-site energy requirements for the erection of the turbine are again taken from (Chataignere & Le Boulch 2003), where it is stated that 556 MJ of energy are required. As there were no details about the nature of this input, it has been assumed that it represents the diesel input to the building machines on site.

6.2.7.6 Component Transportation

In order to define the transportation requirements for the construction of the wind farm, it would be necessary to define the route that the components would be likely to take. Even though no data was available at the time of writing, that described the exact port of arrival for components, assumptions were made as to the most likely route.

The wind turbine components are assumed to be transported from the production facilities in Magdeburg, southern Germany, to the port of Hamburg, north Germany. This distance of 280 km (ViaMichelin 2006), is assumed to be covered by road (40t truck). The components are then shipped from Hamburg, the port in north Germany, to the port of Edinburgh, in Scotland. This distance was estimated to be roughly 900km based on (SeaRates 2008) and the components are assumed to be transported by container ship. The components are then transported by road (40t truck) to their final destination at the Whitelee site, a distance of approximately 80km (ViaMichelin 2006). It should be noted that the wind turbine components that are transported from Germany, do not include the "Foundations" material inputs as they are assumed to be sourced and manufactured locally.

6.2.8 Onshore Wind Farm Operation

The "Wind farm operations" module covers the requirements of the keeping the wind farm operational during its 25 year lifespan. Based on published information, the area taken up by the wind farm is approximately 55 km^2 (CRE Energy Limited & ScottishPower 2006). As part of this process, certain assumptions had to be made about the nature of the maintenance being carried out.

6.2.8.1 Oils and Lubricants

It is a given fact that wind turbines require a replacement of oils and lubricant at regular intervals. For this report, it is assumed that:

- Each wind turbine requires 320 litres of gear oil every 5 years of operation, based on data provided in (Rydh, Jonsson, & Lindahl 2004), (Schnieder & Porter 2006) and (Vestas Wind Systems A/S 2005)
- The lubrication needs of each turbine are of the nature of 16 kg per year, again based on the same reports

6.2.8.2 Component replacement

It is assumed that each turbine will require the replacement of various components (such as bearings, shafts and generator parts) amounting to 5% of its mass, once in its operational lifetime (calculated from (Rydh et al 2004)). As no information about the mass of each component was readily available for this (data being provided in an aggregate form), it was necessary to make estimations based on "rules of thumb" found in (Ancona & McVeigh 2001). In this report, the weights of each wind turbine component are based on percentages of the overall wind turbine weight. Using the provided estimates, the components to be replaced have been modelled based on the following material breakdown.

- 97% of the replaced component weight is attributed to steel
- 2% of the components' materials comprises of aluminium
- 1% of the components mass is composed of copper

6.2.8.3 Inspection and maintenance

For the actual inspection procedure, as well as the replacement of oil, lubricants and gearboxes, the use of a hydraulic crane was added to the process. For the replacement of the gearboxes, once in the wind turbine's lifetime, it was assumed that the crane was required for 8 hrs/turbine (Rydh, Jonsson, & Lindahl 2004). Finally, inspection requirements were based on the assumption that a passenger car would inspect the site every 6 months. The nominal distance travelled for the inspection procedure was based on a “round –trip” from the base of operations of 100 km.

6.2.9 Onshore Wind Farm Decommissioning and Disposal

Little information exists about this phase of the life cycle of wind farms, as in reality, few wind farms have been decommissioned to date. Most of the “first-generation” installations from the late 1980s are still operating and therefore there is a lack of published information on this subject. However, sufficient data on the theoretical disposal of wind turbines and farms is available to be able to model this stage. As such, at the end of its operational lifetime, the wind farm is assumed to be dismantled and the various components sent to different disposal processes. However, as already stated in Section 3.3, it was decided not to include any influence on the lifecycle from the disposal/recycling of the power plants. As such the information included in the following sections is for information purposes only.

6.2.9.1 Wind Turbine Disposal

The final disposal of the wind turbine components is based on (Vestas Wind Systems A/S 2005), (Vestas Wind Systems A/S & Elsam Engineering A/S 2004) and (Elsam Engineering A/S 2004). Actual data from the wind turbine manyfacturer Enercon(Schnieder & Porter 2006) also provided a reference. A summary of possible end disposal routes and assumed recycling rates for the different materials that comprise the wind farm can be seen, in Table 6.8:

MATERIAL SCENARIO	
Steel	100% recovery, (90% recycling and 10% landfilling)
Cast iron	100% recovery, (90% recycling and 10% landfilling)
Stainless steel	100% recovery, (90% recycling and 10% landfilling)
High-strength steel	100% recovery, (90% recycling and 10% landfilling)
Copper	100% recovery, (90% recycling and 10% landfilling)
Aluminium	100% recovery, (90% recycling and 10% landfilling)
Lead	100% recovery, (90% recycling and 10% landfilling)
Glass fibre components	100% incineration of composite material, glass content is hereafter landfilled
PVC-plastic	Deposit of fractions that can be disassembled (assumed 10%), incineration of the rest
Other plastic	100% incineration of waste
Rubber	100% incineration of waste

Table 6.8 Theoretical disposal scenario for an onshore wind farm

Above it has been assumed that 50% of each wind turbine foundation is removed and disposed of. In reality this is not always the case since, depending on the circumstances, various percentages of the foundations are left in place and covered over with earth. The value of 50% is based on the report by (Rydh, Jonsson, & Lindahl 2004). Even though the value in that report is attributed to the concrete component of the foundation (not e.g. the steel reinforcement), it offers an indication that can be used for all the components of the foundation.

6.2.9.2 Wind Farm Operational Wastes

Wastes arising from the operation of the wind farm (oils and lubricants) are assumed to be disposed of at an incinerator for hazardous waste (100% incineration).

6.2.9.3 Wind Farm Site Wastes

Site wastes are assumed to be deposited in an inert landfill onsite.

6.3 Offshore Wind Farm Model

The model developed in this report is based on a large scale offshore wind farm, consisting in a total installed capacity in the region of 1 GW. It is projected that near-future developments of offshore wind farms will have installed capacities in the gigawatt range, given the availability of both the wind resource and the available area for installation (EWEA 2009). An example of such a wind farm is one of the largest offshore wind farms in Europe, known as the London Array. The wind farm is expected to have a capacity of 1000MW when commissioned and will be located in the outer region of the Thames Estuary, approximately 50 km from the coast and be made up of no more than 271 turbines. The wind farm is projected to occupy an area of 245 km^2 in water ranges in depth from 0 to 23 m. The wind farm will be connected to a substation on the mainland through undersea cables.

The model for the offshore wind farm includes all aspects of the wind farm life cycle, such as construction, both site work at seat and the manufacturing of wind turbines, operation and decommissioning at the end of the 25 year operational lifetime. A summary of the offshore wind farm characteristics can be seen in the table below:

LOCATION	OUTER THAMES ESTUARY, KENT
Rated Output (MW)	1001
Number of turbines	152
Turbine Rated Output (MW)	3.6/5
Project Lifetime (years)	25

Table 6.9 Offshore Wind Farm Characteristics

The wind farm model is based on two types of wind turbine, a generic 3.6 MW design as well as 5 MW wind turbine. A more detailed explanation of how these two types of wind turbines are to be sited is given below, in Section 6.3.1.

6.3.1 Energy resource of offshore wind farm location

For the proposed location of the offshore wind farm, detailed wind data such as that used for the onshore location, were not readily available. The U.K. Meteorological Office does provide some data from offshore anemometers, but after investigation it was deemed that the geographical locations of the available stations were not directly relevant to that of the modelled wind farm. As such any available the data from that source was deemed not applicable to this research. Detailed estimates of the wind resource were available however from the London Array Environmental Statement (RPS & London Array Ltd 2005), in the form of frequency distribution outputs from wind farm modelling software. Specifically, information was provided to model the wind energy yield based on Weibull distribution. The data, measured at hub height (80 m) can be seen in Table 6.10:

Sector	C-factor	Mean wind speed (m/s)	k- factor	Frequency
N	9.11	8.11	2.846	4.9%
NNE	10.16	9.12	3.355	5.3%
ENE	9.79	8.75	3.061	8.3%
E	10.35	9.26	3.123	6.5%
ESE	9.51	8.46	2.791	5.1%
SSE	7.38	6.54	2.508	10.3%
S	9.33	8.27	2.441	10.3%
SSW	11.09	9.9	3.014	15.7%
WSW	11.93	10.71	3.325	11.9%
W	10.42	9.28	2.767	11.0%
WNW	10.55	9.41	2.954	6.3%
NNW	10.41	9.28	2.907	5.5%
TOTAL	**10.13**	**9.02**	**2.74**	**100%**

Table 6.10 Breakdown of windrose for offshore wind site

From a check of the frequency distribution it can be seen that the winds are blowing predominantly from the south to west directions, with the strongest component coming from 270 degrees. Based on the roughness estimates already shown previously in Table 4.2 in Chapter 4, a roughness length of 0.0002 (open water) was deemed applicable. Using the Power Law as described in previous sections, a shear exponent of 0.08 was estimated, which is in line with the estimates used by renewable energy consultants Garrad Hassan and Partners Ltd., in their report on offshore wind (Garrad Hassan 2003).

Losses were estimated based on information provided by Garrad Hassan (Garrad Hassan 2003) where an average availability of 93% was assumed for the duration of the project. Similar values were also quoted in (CA-OWEE 2001), where a 95% availability was expected by 2010. Finally, array losses of 8% and electrical losses of 3% was subtracted from the total energy output (Garrad Hassan 2003). The losses assumed have already been outline in Table 6.6, in Section 6.2.6.

Using those estimates and the relevant losses, the energy outputs for the 3.6MW and the 5MW turbines were calculated. A summary of the results for each turbine type can be seen in Tables 6.11 and 6.12, below:

3.6 MW Turbine	
Avg. wind speed (m/s)	9.02
Weibull k-factor	2.91
Weibull scale factor, C	10.10
Annual Gross Turbine Energy Output (kWh)	11,321,668
Avg. daily energy (kWh)	31018
Avg. monthly energy (kWh)	943472
Avg. power (kW)	1292.43
Avg. conversion efficiency	0.22
Capacity factor (not including losses)	35.90%
Annual specific yield (kWh/m^2/yr)	1259

Table 6.11 3.6MW turbine parameters and outputs

5 MW Turbine	
Avg. wind speed (m/s)	9.02
Weibull k-factor	2.91
Weibull scale factor, C	10.10
Annual Gross Turbine Energy Output (kWh)	20,520,162
Avg. daily energy (kWh)	56220
Avg. monthly energy (kWh)	1710014
Avg. power (kW)	2342.48
Avg. conversion efficiency	0.29
Capacity factor (not including losses)	46.85%
Annual specific yield (kWh/m^2/yr)	1646

Table 6.12 5 MW turbine parameters and outputs

The above results showed that the wind farm is expected to have, once losses are included, an average capacity factor of 31.2% and an annual output 2,813 GWh, based on the projected combination of 3.6 MW and 5 MW wind turbines to be installed.

6.3.2 Offshore wind farm construction

While the exact turbine rating is not defined, the maximum dimensions of the wind turbine are set by the project outline. As such, it is stated that the hub heights should be between 85 m - 100 m and a total height no more than 175 m measured from water level[•]. The distance between this level and the blade tip at the lowest point was also limited to no less than 22 m.

6.3.2.1 Project construction schedule

Due to the size of the wind farm, it is expected that it will be built in stages with each stage lasting approximately 18 moths from beginning to commissioning. Due to the timeframe, different size wind turbines are likely to be used for the different stages,

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[•] As the water level does not remain constant the whole year, but is influenced by climatic and lunar changes, the exact definition was measured from "Mean High Water Springs". However, as this definition does not impact the modelling, it will not be discussed further.

based on the availability of design at the time of phase initialisation. For this reason it is expected that the installed capacity of the turbines will range from 3MW to 7MW.

Turbine size	Number of wind turbines	Phases	Total installed capacity
3.6 MW	**185**	**1 + 3**	**666 MW**
5 MW	**67**	**2 + 4**	**335 MW**
			1001 MW

Table 6.13 Total offshore wind farm installed capacity

It must be noted that in the London Array Environmental Statement, the number of turbines installed is higher by six 5MW turbines while the total wind farm installed capacity is 1031MW. However, in the notes of the report, it is clearly stated that *"the project will not install any more turbines than are necessary to achieve an installed capacity of 1000MW"*(RPS & London Array Ltd 2005). As such, the decision was made to remove the required amount of turbines to bring the installed capacity down to 1000MW.

6.3.2.2 Foundation types

A major point that was not clearly defined in the London Array's Environmental Statement was the type of foundation to be used at the wind farm. In order to locate the wind farm, the wind turbines will need to be installed on the sea-bed using specially designed foundation bases. The choice of foundations is influenced by various factors, including the type and height of the hub, wind and wave loading, the soil conditions on which the foundations will be positioned, transportation, cost and material requirements and installation equipment (RPS 2005). A representation of the different options can be seen in Figure 6.8 (IEA CADDET & Danish Energy Agency 2000).

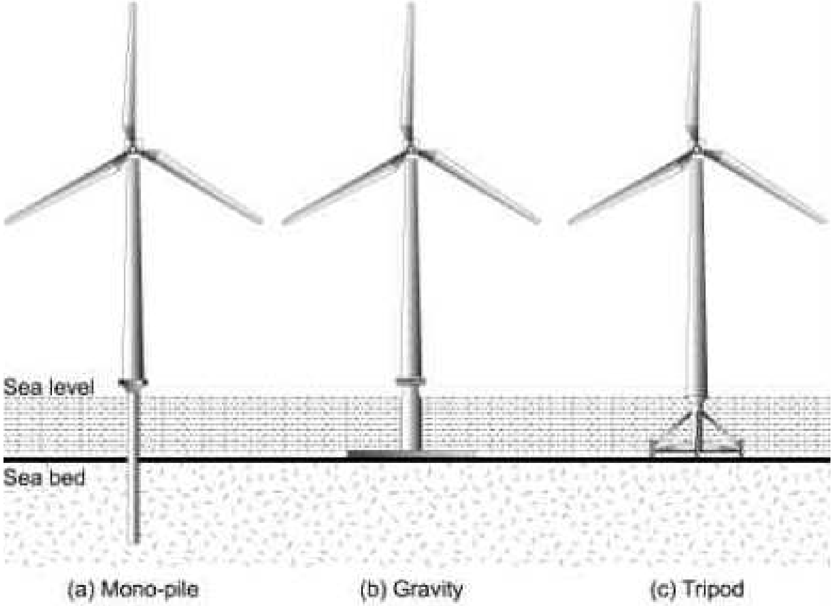

Figure 6.7 Choices of foundation for offshore wind turbines

The three main bases for offshore installation under consideration are:

Steel monopile – a hollow steel cylinder driven into the seabed

The steel monopile is the most common foundation type used for offshore wind turbines, and is based on the experience gained from offshore oil rigs. Monopiles are usually driven into the seabed from a jack up barge using hydraulic hammer. A typical mono-pile foundation consists of three different parts: the pile itself; a transition piece between the pile and tower; and a boat landing for service boats. The steel monopile would be pre-fabricated onshore from steel sheets that are rolled at manufacturing facilities to create the structure. A 10m long transition piece consisting of a piece of steel pile equipped with a flange is required to attach to the wind turbine tower. Driving a single monopile into the seabed can take between 1-8hrs depending on the site conditions (RPS & London Array Ltd 2005).

Using a monopole foundation offers the following advantages:

- The installation is usually quick when the proper equipment is available;
- The piles themselves are very simple to produce;
- The seabed needs little or no preparation, such as digging, levelling etc;
- The piles are more or less insensitive to erosion, and therefore do not require specific treatment and/or site preparation.

Such a system, however, can involve a substantial amount of welding in an offshore situation.This system has been used for wind turbines off the coast of Gotland in Sweden. (IEA CADDET & Danish Energy Agency 2000).

Gravity-based foundation – A large concrete/steel structure that sits on the seabed and remains in position purely by the weight.

Concrete gravity foundations are typically installed in water depth up to 30m. The idea behind this type of foundation is that the construction forms a wide base than is sufficiently heavy to ensure the wind turbine stays in place even under the heaviest loading. There are different kinds of concepts for this foundation in use today: a hollow concrete caisson on top of a thick plate which is then filled with material (usually sand or gravel) to reach the required weight and a version with an even thicker plate which is made heavy enough to position the structure by itself. The foundations would be pre-manufactured onshore and then shipped by barge or floated to the wind farm location to be positioned. (RPS & London Array Ltd 2005) (IEA CADDET & Danish Energy Agency 2000). The main disadvantages of the concrete caisson method are found in the need to increase their weight as the water depth increases. Also the transition piece between the concrete foundation and steel is hard to produce and can be quite costly. The drawback with the steel caisson version is the need to ballast them with heavy minerals. (IEA CADDET & Danish Energy Agency 2000)

Tripod Foundation – a frame of three or more legs pinned to the seabed usually using driven steel piles.

The steel tripod has been used extensively in the offshore oil and gas industry but has not yet been used for wind turbines. The concept involves a steel tube construction above the seabed and three piles driven into the seabed, in similar fashion to the monopile foundation. The tripod concept is better suited to deeper water where a monopile would have to become so large that it could not be handled and installed using current technology. Equally, a caisson would become uneconomically large. For such depths, a multiple footing option would be more attractive, either in the form of a three leg or four leg foundation (B.W.Byrne & G.T.Houlsby 2006).

Like the steel gravity foundation, the tripod system can be produced onshore at existing shipyard facilities and floated on a barge to the final location.

The presence of obstacles on the seabed may alter flows around the foundations of the wind turbines which can lead to scouring of the seabed. As a result, scour protection material may be placed around the base of the foundations and cable route to minimise the impact. The wind turbines are connected to each other in groups by array cables that connect these clusters to offshore substations. Several of these clusters are connected to each substation. It is expected that for the size of the wind farm, approximately 5 substations will be required. Each substation is used to increase the voltage of the before transmitting the power along the 50km submarine transmission cable to onshore facilities. The onshore substation would house up to six transformers, required to transform the electrical output of the wind farm to 400kV, which is the likely operating voltage of the National Grid transmission lines. The onshore substation will also house the auxiliary services building as well as the switching equipment required for connection to the National Grid (RPS 2005).

Based on this information, two models of wind turbines were created to cover the 3.6 and 5 MW ratings. Since no exact life cycle inventory (LCI) data was available for either rating, the models were created by combining manufacturers' data with existing database material inventories to create representations of the designs for the purposes of this study.

6.3.2.3 The 3.6 MW wind turbine

At the time of writing, there were relatively few wind turbines rated at this level commercially available. The two main contenders in this category are General Electric with its 3.6 MW Offshore Series wind turbine, which is based on an upgrade of its existing 1.5 MW turbine, and the Siemens SWT-3.6-107 series turbine. Of the two, the Siemens model has already been installed in Europe and was thus chosen as the modelling guideline for this study. The main technical characteristics can be seen below:

TYPE	3 bladed upwind horizontal axis	
Rated output	3600	kW
Diameter	107	m
Swept area	9000	m^2
Rotor speed	5-13	RPM
Blade length	52	m
Shaft torque	4300	kNm
Low speed torque	36.1	kNm

Table 6.14 Technical characteristics of modeled 3.6MW turbine

The main source of data on wind turbine material requirements was the "Wind Turbine Systems" part of the ECLIPSE project (Chataignere & Le Boulch 2003), which contained a materials database for 600 kW, 1500 kW commercially available turbines and extrapolated generic data for a 2500 kW and 4500 kW wind turbine. In this research, due to the lack of data on a 3.6 MW, it was decided to scale up the information available for one of the existing designs. The rules used for estimating the masses of the different components were taken from a study carried out in the United States, by the NREL (Fingersh et al. 2006). The report contains basic scaling rules based on general wind turbine parameters (rotor radius, installed rating etc), and was used to provide the component masses for a 3.6 MW (see Appendix C). Once the general masses were established, the material breakdown for each turbine component was established, by scaling proportionally the data for the ENERCON E-66. An exception to this scaling rule proved to be the generator. From the information available on the Siemens wind turbine, and the generator manufacturer's information (Winergy AG 2007), it was obvious that the NREL rules were below the lower limit of generator component weights. This can be explained due to the lack of information on the low-speed shaft torque (required by the scaling equations). As such the decision was made to take an average of the published weights and use that to scale the generator component. The information for the offshore grid connection requirements were based on the ECLIPSE data which in turn was based on an unpublished detailed study by the utility Electricite de France (EdF). However, it was unclear whether the module contained the onshore components of the grid connection. In order to incorporate this aspect of the wind farm construction, the onshore grid connection was based on a scaled up version (based on turbine ratings) of the module for the 2.5 MW turbine. As such, the offshore material requirements were deducted from the scaled-up onshore grid connection material list, therefore giving an estimation of the materials required to construct the onshore grid infrastructure. This decision is based on the assumption that the overall grid connections of the 3.6 MW turbine will be analogous to those of the 2.5 MW, with the materials split between the off- and onshore connection infrastructure.

The foundations were modelled using a combination of the information from the ECLIPSE Project and the Environmental Statement for the L.A.L. The ECLIPSE Project provided information about the required foundations for a 2.5 MW offshore wind turbine, which were then scaled up (based on power ratings) for the 3.6 MW turbine being modelled. However, when comparing the scaled mass of materials to the generic values provided by the London Array Environmental Statement, it was found that there were some discrepancies between the quantities estimated by the two reports. Specifically, although the estimates in both reports for the gravity (caisson) foundations were in accordance, it was found that the scaled up versions of the monopile and the tripod-style foundations did not include the use of concrete, as detailed in LAL, while the ECLIPSE general estimates of material requirements for the latter were significantly lower. In both cases, it was assumed this extra concrete in the LAL report, relates to the connecting piece between the tower and the foundations. The discrepancy for the tripod foundations has not been explained but in the interest of consistency, the values from the ECLIPSE report were used, as the LAL cited no references for their information.

In order to incorporate the concrete into the material estimates, it was deemed necessary to use a scaling rule that could relate the amount of concrete to the other estimates. As such, the amount of concrete was scaled between the two reports, using their equivalent ratios of steel (i.e. same ratio for the concrete as for the steel data). An exact breakdown can be seen in Appendix C.

Assembling/Manufacturing requirements

The manufacturing and assembling requirements for the 3.6MW wind turbine were based on the scaling up of the equivalent requirements of the 2.5MW turbine modelled in ECLIPSE. The scaling was carried out based on the total estimated mass of the wind turbines, as opposed to their relative power ratings. The energy requirements for the assembly of the wind turbine can be seen in Appendix C.

Onsite Erection requirements

The onsite requirements for the erection of the 3.6 MW turbine are based on data for the ECLIPSE 2.5 MW turbine scaled using the ratio of relative masses. This gives a requirement of approximately 1524 MJ, assumed to be expended in the form of diesel fuel for the construction equipment.

6.3.2.4 The 5 MW wind turbine

There are a very limited number of manufacturers that offer wind turbines in the 5MW and above category, with most designs in the prototype stage. However, as wind power continues to grow, it is expected that these turbine ratings will become more common. In this work, the decision was made to model a 5MW wind turbine because:

1. It was the size originally defined in the Environmental Report for the L.A.L.
2. The larger wind turbines (i.e. > 5 MW) are still in the development phase.
3. The ECLIPSE Project contained data on a 4.5 MW turbine so it was decided that it would be more accurate to scale this existing model up to 5 MW, rather than higher.

Based on the above considerations, a 5 MW model was created based on the on the specifications of the REpower 5M (REpower Systems AS 2007) and the data available for the 4.5 MW. However, two departures from the ECLIPSE data were deemed necessary. Firstly, the blades were calculated using the NREL scaling equations which applied to the “advanced case”, which was based on turbine blades manufactured by LM Glasfiber A/S. Since the REpower 5M was developed jointly with LM Glasfiber, this move was considered appropriate and more representative than using generic modelling data. The other main departure from the use of available data, was the modelling of the tower unit, that based again on NREL equations. This was undertaken because the original ECLIPSE data modelled the tower using an all-concrete design. Although REpower provides the option of a concrete/steel-concrete hybrid tower, it was felt that for offshore applications, their steel tower was a more likely option.

For the estimation of the data for the 5 MW turbine, a straight scaling rule was used based on the 1.5 MW turbine and the ratio of the installed capacities of the turbines (except for the two components mentioned above), as in the original ECLIPSE datasets (Chataignere & Le Boulch 2003). The grid connection modelling data suffered from the same uncertainties as those highlighted earlier in the 3.6 MW model. As in the case of the 3.6 MW model, the type of foundations used for the installation of the offshore wind farm were not defined.

Assembling/Manufacturing requirements

The manufacturing and assembling requirements for the 5 MW wind turbine were based on the scaling up of the equivalent requirements of the 1.5 MW turbine modelled in ECLIPSE. The scaling was carried out based on their relative power ratings. This method was used in ECLIPSE report for the calculation of the requirements for their 4.5MW turbine, and therefore seen as more consistent than using the scaling based on relative weights.

Onsite Erection requirements

The onsite requirements for the erection of the 5 MW turbine are based on data for the 1.5 MW turbine scaled using the ratio of relative masses, instead of the power rating ratio. This approach was taken as using the ratio of power ratings did not reflect the increased complexity in what is in effect a "step-change" in the size of turbine manufacturing.

6.3.3 Offshore wind farm component transportation

The calculation of the transportation requirements are dependent on the type of foundation chosen. For the purposes of this study, generic distances for the transportation of the components were assumed (100 km on land, 900 km by sea since construction is assumed to be in Germany and 25 km to final site)

The components are assumed to be transported by 40 t truck on the road and barge tanker for sea transportation and for the move to the final erection site.

6.3.4 Offshore wind farm operation & maintenance

The operational requirements of the wind farm are based mainly on the assumptions used in the ECLIPSE work. The case used for this work, reflects the maximum maintenance scenario, which stipulates a replacement of 15% of the nacelle (on a material mass basis) and 1 blade for each turbine, during the wind farm's life-cycle. The original data seems to imply that the ECLIPSE project calculates the "maximum maintenance" requirements as an approximate percentage of the mass of the replacement components with respect to the original components. This approach was followed for the calculation of the requirements for the replacement components for the scaled (3.6MW and 5MW) turbines. Real life information from the Scroby Sands wind farm would seem to indicate that the above assumptions are within reason, as experience there has shown (replacement of gearboxes, bearings and generators within the first year of operation) (E.ON UK Renewables 2006)

For the 3.6 MW wind turbine, the manufacturing/assembly requirements for the maintenance components were scaled on the ratio of the mass of the replacement components (1 blade and 15% of the nacelle) compared to the original component masses, using the original manufacturing/assembly requirements. The on-site erection maintenance requirements were based on the same mass ratio assumption. For the 5 MW wind turbine maintenance manufacturing/assembly requirements, the values were estimated using again the ratio of the mass of the replaced components as a scale factor. The onsite erection requirements for maintenance were also scaled on mass ratios (the replaced components represented 9% of the original turbine mass, so it was assumed that they required 9% of the original energy requirements)

With respect to the oil and lubrication needs of the two wind turbines under consideration, the oil requirements for the 3.6 MW are taken directly from information submitted as part of the Lewis Wind Farm application process (Lewis Wind Power Limited & AMEC Wind Energy 2006), where it is stated that the turbine requires 720 litres of oil. For the 5 MW model, as no information was directly available, a scaled up version (according to their rated capacities) of the 3.6 MW's oil requirements was assumed. In both cases it is assumed that the oil is changed every 8 years.

The transportation requirements for both wind turbine models were calculated using the same distances as for the original erection and the masses of the replacement materials (i.e. 15% of the nacelle, 1 blade and oil requirements). A small vessel is also assumed to be used to conduct maintenance visits, estimated to take place 4 times a year (IEA CADDET & Danish Energy Agency 2000).

6.3.5 Offshore wind farm decommissioning and disposal

As in the case of the onshore wind farm, no consideration was given to the effects of the end-of-life scenarios on the power plant's lifecycle performance. As before the information on this lifecycle stage was provided for completeness. The decommissioning plan is based on the information provided in (RPS & London Array Ltd 2005):

Turbines

Before removal from site, all the turbines will be prepared by disconnecting them from the network, making safe any loose structures and removing all liquids from the structure. Once this preparation has been carried out, it is assumed that a reversal of the installation process will be used to remove and transport the wind turbine components to shore.

Offshore substation

Each substation will be removed from site and transported to shore by barge, where it will be further dismantled. As with the wind turbines, the substations will be disconnected, while both liquids and any SF_6 gas will be evacuated and returned to the manufacturer for recycling. The foundations will be dealt as detailed below

Foundations

Monopile foundations: These foundations will be removed by cutting the monopile at an appropriate depth such that any length that remains in the seabed cannot be uncovered easily. The monopile will be cut, through the use of high pressure water/grit jetting from inside the monopile.

Gravity-based foundation: It is expected that these foundations will be fully recovered and returned to shore.

Tripod foundations: These foundations will be treated in a similar fashion to those of the monopile style.

The ECLIPSE report contains information on the disassembly energy and material requirements of the wind turbines. In both the cases of the 3.6MW and 5MW, the disassembly energy was equated to the assembly/manufacturing energy for lack of any more specific information.

Disposal scenario

Limited information is available on the disposal of wind farm materials, as also stated in the case of the onshore wind farm. In previous works (see (Egon T.D.Bjerregaard, Sven-Erik Thor, & Risø 2002)), it is claimed that the large composite blades constitute a big problem from a disposal point of view, as only 20 % of recycled materials can be used successfully in other products. However approximately 80 % of a wind turbine system including cabling can be recycled.

6.4 Summary of wind farm modelling

In the previous sections, the modelling methods employed to create the onshore and offshore wind farms have been laid out. Thus, it can be seen that due to the key differences between onshore and offshore wind farm designs, different modelling approaches needed to be adopted. In both cases however the assumptions and approximations have been laid out to ensure clarity.

As stated in the introduction to the chapter, offshore wind farms usually employ specific wind turbine models that are both larger and more complex than their onshore counterparts. The necessity to be steadily positioned out at sea also has a direct impact on the type of foundations used and the erection procedures employed. Thus different procedures and scaling relationships are required to model offshore models, while the offshore foundations require specific data collection and manipulation. Conversely, the lack of detailed site measurements for the onshore wind farm has necessitated the use of a scaling method utilising reference data from nearby reference stations.

The resulting models however are believed to accurately reflect real-life conditions and are therefore provide a good basis for computations based on the wind power life cycle.

7. Results of research

7.1 Introduction

This chapter demonstrates the results of the application of the methodology, outlined in Chapter 3, to the models that were developed for the wind farm and the nuclear power plant in the previous two chapters. The chapter is arranged so that for each metric used in the assessment, the performance of each energy supply system is assessed and then compared to the other. Following this initial assessment using the main indicators defined for this analysis (energetic and emissions-related), a parametric analysis of both wind and nuclear power is carried out. This allows for the calculation of a range of values for the main parameters. The parametric analysis is based on a range of variations to the baseline input values, which are deemed likely using available information in the relevant literature as guidelines.

Once a range of values for the main parameters has been established, the avoided carbon dioxide emissions from the implementation of the wind and nuclear power plant are assessed in a separate section (as per the guidelines in Section 3.5.7).

7.2 Energy metrics

The metrics relevant to Net Energy, as previously described in Chapter 3, are calculated for each of the life cycles under investigation in this research and are outlined in the following sections.

7.2.1 Total energy requirements

One of the metrics that is of primary importance in the assessment of the net energy of energy supply systems is that of the total primary energy requirement for each technology, also previously defined as the "Cumulative Energy Demand" (CED). This metric encompasses all the direct and indirect energy inputs into the systems under investigation, and, as a first instance, provides an indication of which system has a greater impact on the energy surplus of the background system (i.e. the national economy or in a more global sense, the available energy resources of the planet). Thus it can be argued that the CED is especially meaningful in a context where the depletion of energy resources only permits a certain amount of resources to be diverted into the construction of power plants which provide a secondary energy source, that is to say, electricity.

7.2.1.1 Nuclear power lifecycle CED

The first indicator to be investigated was the total energy requirement for the nuclear power lifecycle base-case, as this provides the starting point for all other energetic indicators. The CED for the nuclear power model was calculated to be 54.5 $PJ_{prim.}$. This included all the energy requirements (both direct and indirect), over the whole life cycle, for the power plant to operate at an average load factor of 85% for 60 years, at a gross rated capacity of 1117 MWe. A breakdown of the energy requirements per lifecycle stage can be seen in the following figure:

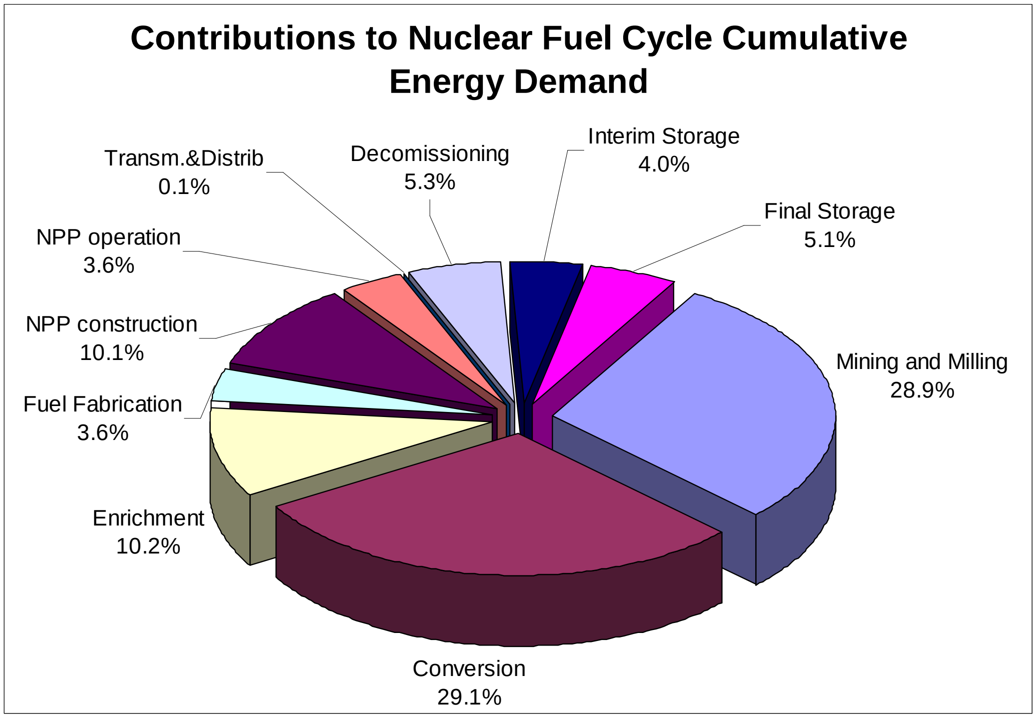

Figure 7.1 Breakdown of nuclear power CED per lifecycle stage

From Figure 7.1 above it can be seen that the "Front End" of the nuclear life cycle, which comprises of the stages of mining and milling, U_3O_8 conversion, UF_6 enrichment and UO_2 fuel fabrication, accounts in total for approximately 72% of the total energy requirements. The actual operational stages of the nuclear power plants life cycle, which incorporate the NPP construction, electricity generation and transmission and distribution phases of the life cycle, make up less than 15% of the total. The remaining 14% - 15% of the life cycle energy requirements is attributable to the "Back End" of the nuclear life cycle, which covers the NPP decommissioning phases as well as the interim storage and final disposal of spent fuels and wastes.

Concentrating solely on the "Front End" phase, the largest relative contributors are the phases of mining/milling and yellowcake conversion to uranium hexafluoride, with approximately 41.7% and 39.5% of the stage respectively. The enrichment stage is next with 13.8% of the "Front End" total, followed by the phase of final fuel fabrication with 4.8%. The relatively low contribution of the enrichment stage to the "Front End" total energy requirement is not fully in accordance with the results found in other studies. Specifically, in (Vattenfall AB Generation Nordic Countries. 2004), as quoted in (WNA 2005a), the enrichment stage makes up more than 68% of the "Front End" and approximately 53% of the total life cycle energy requirements. Also in the case of (ISA 2006), the enrichment stage represents more than 40% of the total life cycle energy requirements. In other studies however, as in the work carried out in (AEA Technology & British Energy 2005) and in the World Nuclear Association's own estimations (WNA 2005a), the enrichment stage has less than 20% of the total energy demand attributed to it. The deciding factor appears to be the type of process which used to enrich the fuel (i.e. centrifuge or diffusion process) and the source of energy supplying the enrichment facility. The diffusion process is a significantly more energy-intensive method and the difference in energy requirements per SWU can be in the region of 50 times higher (commonly quoted values for the diffusion method average around 2300-3100 kWh_e/SWU as opposed an average of 290 kWh_e/SWU and values as low as 40 kWh_e/SWU for the centrifuge method (ISA 2006)). In this current work, the enrichment is assumed to be carried out using the centrifuge method and hence the relative energy requirements for this stage are much lower than in other studies. Also the energy requirements for the centrifuge, as described in Chapter 5, were among the lowest quoted in the above literature, a fact probably related to the age of the data presented in those other sources. Finally, as stated previously, another influencing factor is the source of energy supplying the enrichment facility. If the facility is being powered by the country's national electricity grid, the generating mix will effect the primary energy requirements of this stage. If the mix is heavily based on fossil fuel power generation, then the primary energy requirements will be higher than one based mainly on renewables (and depending on the accounting methodology, nuclear power). In conclusion, the lower relative percentage of energy requirements attributed to the enrichment stage can be traced to the use of the centrifugal method of enrichment (as used in the base-case scenario) and the fact that more up-to-date data was used for the operational requirements of these facilities. The effect that different enrichment methods have on the lifecycle will be better illustrated by the results of a parametric analysis carried out in subsequent parts of this chapter. In this work it has been assumed that the enrichment facilities are located in France and the U.K. As mentioned in the modelling section, data sources stated that the French enrichment facilities are supplied directly by a nuclear power station. In the U.K. facility however, it is assumed to be supplied by country's national grid.

Of special interest is a description of the milling and mining phase, due to the complexity of interaction between the contributing components. A further breakdown, to facility level, of the energy requirements for the mining and milling phase produces the following figure:

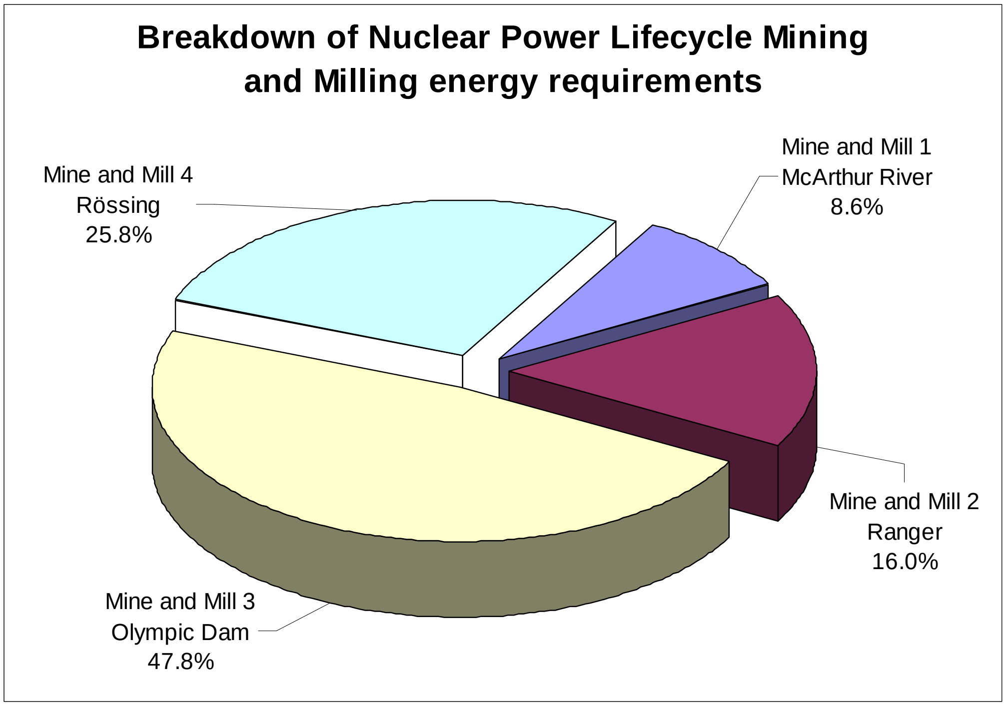

Figure 7.2 Mining and milling energy requirements

It can clearly be seen that the Olympic Dam facility in Australia is responsible for nearly 48% of the stage's energy requirements, followed by the Rössing mine in Namibia. Both McArthur River and Ranger mines in Australia account for lower percentages of the stage's energy inputs. As stated in the chapter on the modelling of the nuclear fuel cycle (Chapter 5), all the mines are assumed to supply equal amounts of U_3O_8 to the overall life cycle requirements (25% of the total each), so any differences in the energy requirements are directly related to each mine's operating characteristics. These include such issues as type of mine (open pit, underground), ore grades, extraction methods etc. As a result, it is not surprising to see that Olympic Dam, which has the second lowest ore grade of the 4 mines studied, is the facility with the highest energy requirements. Another major contributing factor is the fact that although the uranium ore is a by-product of the mine's main produce (i.e. copper), the attribution of a conservative percentage of the mine's energy requirements to the uranium ore (i.e. disproportional to the fraction of uranium ore as a percentage of the total mine output; see Chapter 5), has meant the energy requirements are higher than those of mines with lower ore-grades (i.e. the Rössing mine). The Rössing mine, on the other hand, has both a marginally lower ore grade as well as an energy supply based on electricity from the Namibian grid which is predominately hydro-powered (although when importing from the S. African grid, has high percentages of coal-fired power). Thus, it is not unexpected that it might have lower primary energy requirements than Olympic Dam. Finally, it can be noted that McArthur River has the lowest percentage of the total energy requirements, despite the use of conservative energy inputs. It is important to note that due to the high uranium concentrations of the ore at McArthur River, the ore blend is diluted using mill tailings (from the processing of Key Lake's own deposits, which have since been depleted) from 17.3% to 4% U_3O_8 for milling (IAEA, NEI, WNA, & UNECE 2006). This is done to make it compatible with yellowcake production from other facilities.

Returning to Figure 7.1, in the electricity generation phase of the lifecycle, that includes the construction of the power station, its operation and the transmission of the electricity, it can be seen that the operational requirements are among the lowest ranked stages of the life cycle. Construction of the power plant represents 10% of the total energy requirements, while transmission requirements are negligible. It should be noted, that as the power station is assumed to supply its own electricity requirement, this is reflected by a reduction in the station's power capacity, rather than by attributing the life cycle impacts of nuclear generation to the current lifecycle. In other words, the primary energy requirement of nuclear-generated electricity are not added to this lifecycle as would have been the case were it to be assumed that the electricity was supplied from nuclear sources, external to the power station. This is a point that is rarely clarified in other studies on the subject and certainly will cause some differences between the values quoted.

With regards to the "Back End" phase of the nuclear life cycle, it is interesting to note that the power plant decommissioning stage's requirements are on-par with those of the rest of the stages in that phase. As such, both the interim storage as well as the final storage of the nuclear waste each contribute only between 4-5% of the life cycle total. This particular phase of the life cycle has been open to serious controversy, mainly due to the fact that all studies are, by necessity, based on speculative data. As no country has yet implemented an integrated waste disposal programme, currently no concrete operational data exists to model this stage. Despite the fact that this work utilises one of the most comprehensive data sets for the U.K., the modelling of this stage represents an assumption of future procedures and conditions. The low relative importance of the "Back End" is also reflected in the work carried out by (ISA 2006), which is based on a similar data set (if one excludes the energy inputs required for the processing depleted uranium, a stage usually not covered by reports on the subject[*]).

However, assuming that the scenarios and associated data sets are plausible, it is interesting to note that the final storage (as modelled based on the phased repository concept), places a fairly limited burden on the total life cycle energy requirements. This no doubt can be traced back to the assumption of a 50-year active monitoring regime, after which the facility is sealed off, with a minimum level maintenance carried out from then on. Given that this stage includes all the energy and material requirements for waste disposal, this would seem to indicate that, from a energetic point view at least, this section poses relatively little problems. The fact that Interim storage on the other hand, represents an almost equal fraction of the energy demands of the Back End as Final Disposal, shows that there is little incentive from an energetic point of view to keep waste in this stage of its life cycle. Given the similar energy requirements but the difference in assumed time scales between the two stages (5 years in interim and 50+ in storage), the results seem to indicate that the maintenance of waste in interim storage should not be prolonged any more than completely necessary.

7.2.1.2 Wind power lifecycle CED

The total life cycle energy requirements for each form of wind power (onshore and offshore) are treated separately in this section.

Onshore Wind

From the model generated in the Simapro software, it can be seen that the CED for the onshore wind farm is approximately 2.63 PJ_{prim}. A detailed breakdown of the main life cycle phases and the percentage of the total energy demand they represent is shown in the figure below.

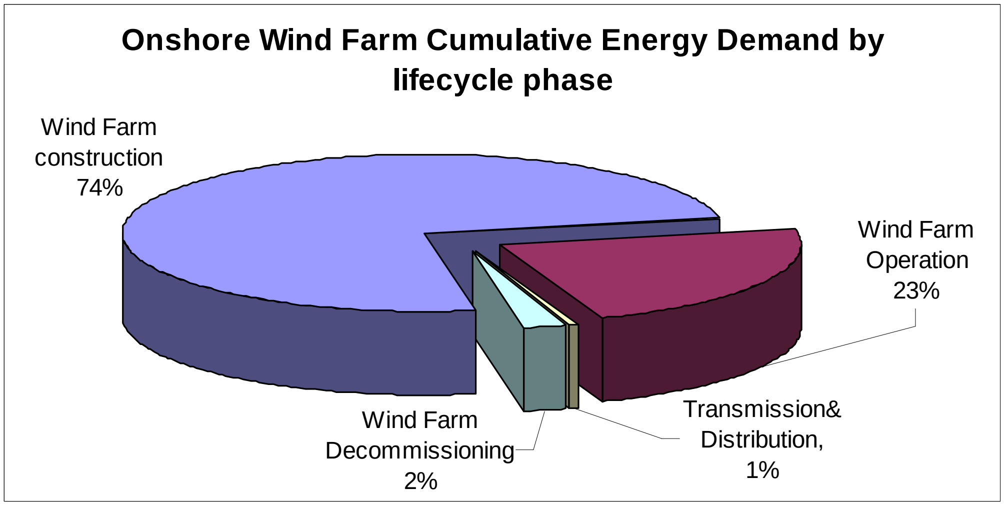

Figure 7.3 Breakdown of onshore wind farm energy requirements per life cycle phase

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[*] The effect of depleted uranium reprocessing will be discussed in this work in a later section of this chapter.

As can be seen clearly in the above figure, the wind farm construction phase (which encompasses the manufacturing of the wind turbines as well as the on-site erection of the wind farm), represents, by far, the largest energy user of the life cycle. This phase is then followed by the energy requirements for the operation of the wind farm (almost 23%), while both transmission requirements and decommissioning requirements are below 3% in total.

The decommissioning and disposal phase of the wind farm is a phase of the lifecycle for which data is limited. The main reason for this is that, to date, very few wind farms worldwide have reached this point in their lifecycle (Rydh, Jonsson, & Lindahl 2004). In this work it has been assumed that certain percentages of the components of the wind turbines are recycled or scraped (the percentages are outlined in Chapter 6). As stated there however, the positive effects from recycling are attributed to the user of the recycled material not the lifecycle that created them. Therefore, the decommissioning phases includes only the energy required to dismantle the wind farm and for transportation.

A closer look at the wind farm construction phase reveals that the most important component is the wind turbine itself, with on-site erection playing a minor role. The breakdown of the wind turbine into its constituent parts, as modelled in this work, is shown in Figure 7.4. From the chart, it can be seen that the largest fraction of the energy demand for this section is associated with the tower unit (approximately 27%). This is not surprising as it has been assumed that the tower is manufactured from various steels, all materials with high embodied energy values. The rest of the components that make up the wind turbine each represent an almost equal slice of the remaining 73%. In each of these components, there are materials with high embodied energies. As a result, despite the difference in the mass of the components, from an energetic viewpoint, they account for similar proportions of the total wind turbine energy demand.

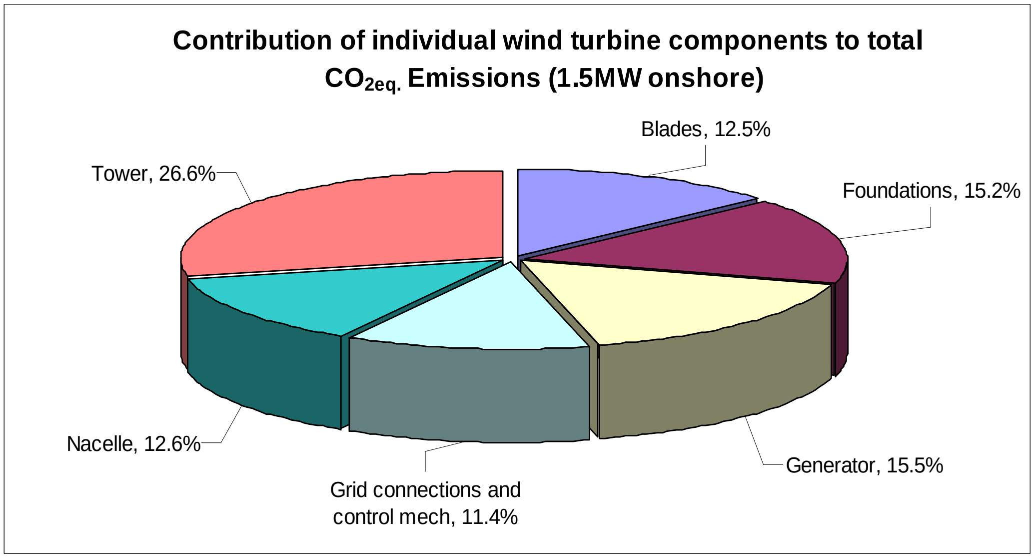

Figure 7.4 Breakdown of onshore wind turbine total energy requirements

Offshore Wind

The offshore wind farm, as modelled in this research, demonstrated a cumulative energy demand of approximately 14.5 PJ_{prim}. The high energy demand of this wind farm, in comparison to the onshore one, is attributable both to the much larger scale of the installation, as well as the fact that the building requirements are much higher than the equivalent onshore ones. As can be seen from Figure 7.5, the wind farm's construction phase outweighs all other stages.

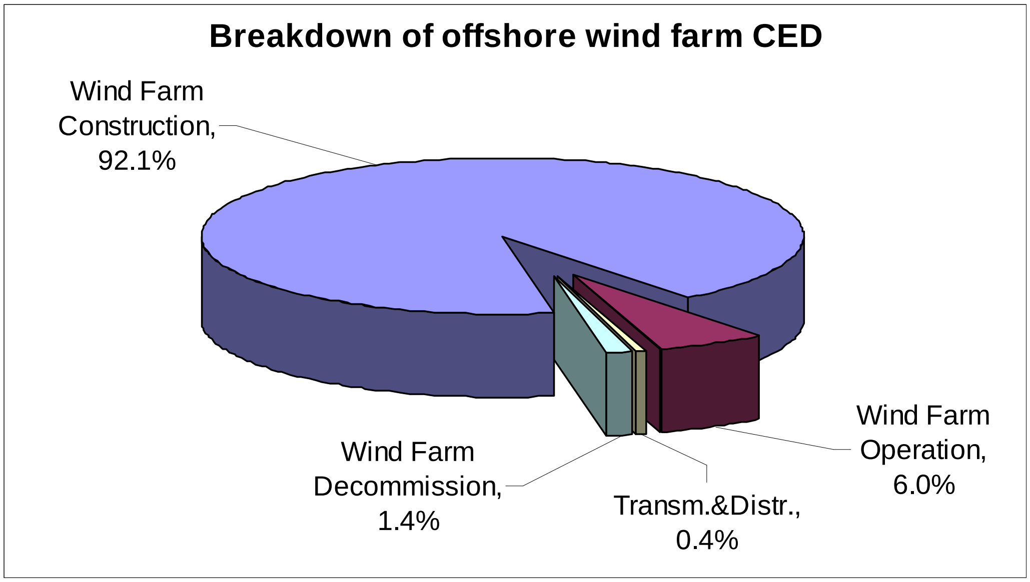

Figure 7.5 Breakdown on offshore wind farm energy requirements per life cycle phase

In this phase, the embodied energy in the components of the 3.6 MW and 5 MW, the energy requirements for manufacturing of the wind turbines as well as their onsite assembly are combined to provide a single energy requirement. Breaking this stage down further into its component parts, in other words, into the two different types of wind turbine that comprise the wind farm, Figures 7.6 and 7.7 show the results for the 3.6 MW and 5 MW turbines respectively. It is important to note that the wind farm decommissioning phase contributes a negligible amount to the total energy requirements. This is due to the assumptions made about this stage which follow exactly the same line as those of the onshore wind farm.

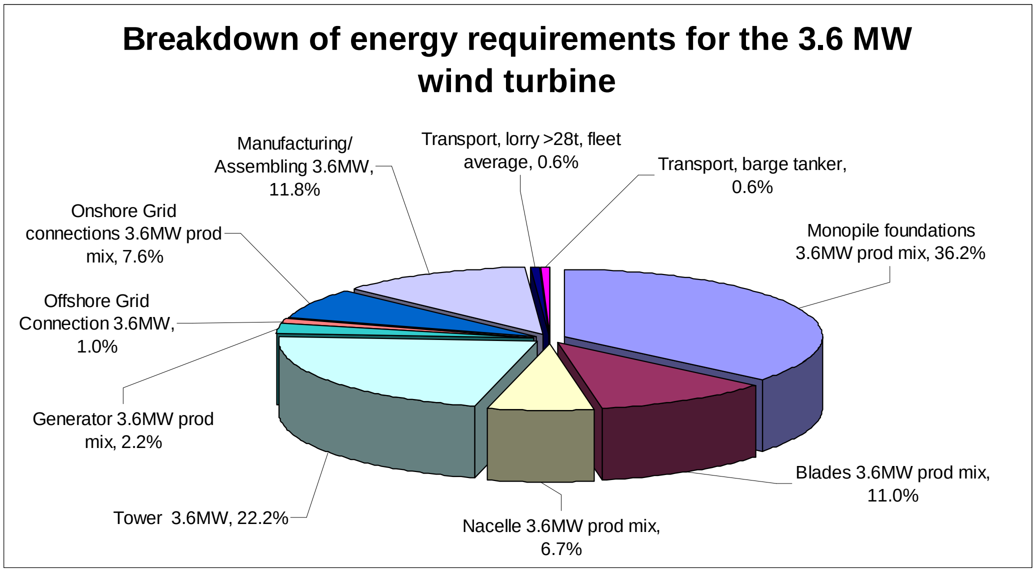

Figure 7.6 Breakdown of the energy requirements for a 3.6MW turbine

From the above diagram above, it can be seen that the monopile foundations represent the highest percentage of the total energy requirements, followed by the wind turbine tower unit. This is to be expected as both components are heavily reliant on materials with high embodied energy such as metals and specifically steel.

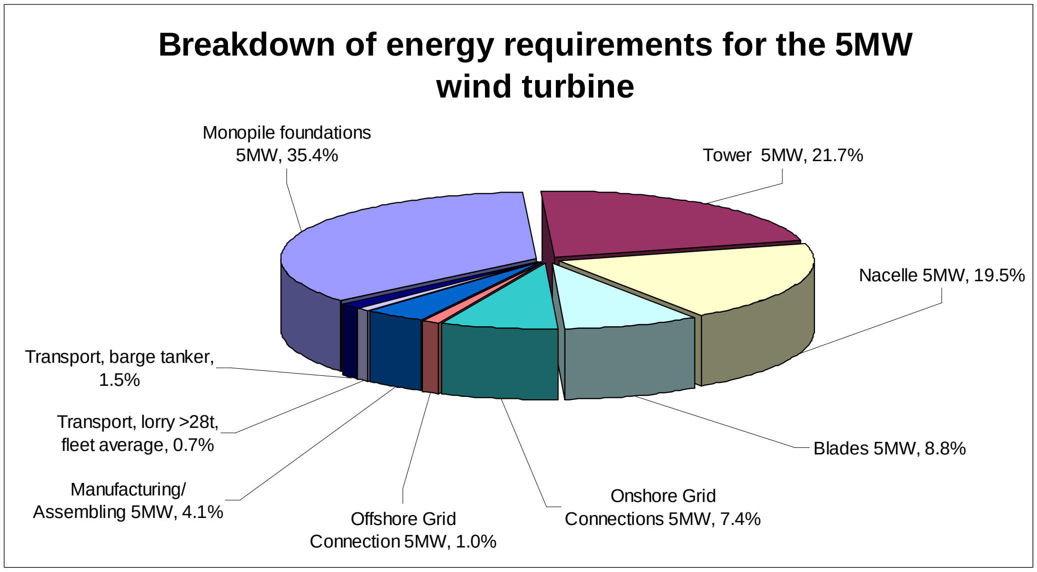

Figure 7.7 Breakdown of the energy requirements for a 5MW turbine

For the 5 MW wind turbine, a similar breakdown of energy requirements can be seen as previously for the 3.6 MW version. The biggest difference in relative energy attributions between the two wind turbine types can be seen if the relative percentages for the nacelles are compared. There it can be seen that the nacelle of the 5 MW turbine has higher relative energy demands in comparison to the 3.6 MW nacelle. However, this discrepancy is due to the modelling assumptions used which were different for the two turbines (as detailed in Chapter 6), rather than any evident fundamental difference in the design between the two turbine types. As was stated in

Chapter 6, different baselines were used for the scaling of the 3.6 and 5 MW turbine models, creating therefore the differences in energy requirements for the same component.

7.2.1.3 Comparison of the Cumulative Energy Demand

As can be seen from the above sections, the nuclear power fuel cycle represents, by far, the largest cumulative energy demand of the three energy supply systems considered in this work. This lifecycle is then followed by offshore wind and finally by onshore wind which has the lowest total life cycle energy requirements.

An important addition has to be made however to the definition of Cumulative Energy Demand (CED) as a parameter. Whereas for wind energy the CED is largely indifferent to the final output of the wind farm, in the case of energy supply systems based on the consumption of some non-renewable secondary fuel (i.e. a fuel that requires processing before it can be used in a system to generate electricity), the total energy inputs are directly correlated to the proposed energy output of the system. This fact can be seen clearly in the case of the nuclear lifecycle, where uranium ore requires significant processing before it can be utilised as a fuel in a nuclear power plant generating electricity. The production of electricity in the nuclear power plant is directly related to the amount of uranium fuel used, which in turn dictates the quantity of uranium required and hence the total energy requirements for the processing of the fuel. As such, the CED of the nuclear lifecycle is directly related to the assumptions and estimations made about its energy output. Even in the case of energy supply systems based wholly on renewable energy sources such as wind or solar power, the CED only serves as an absolute indicator of energy consumption for the system but does not provide information that can be used in a comparison between systems working on different operating cycles. This once again is due to the energy output of the systems being investigated. Thus, it is perfectly possible for two systems to have similar CED but produce completely different energy outputs (or different forms of energy outputs) which in turn indicate a difference in lifecycle energy conversion efficiency. This conclusion effectively dictates that the CED for different energy systems is only valid as a point of comparison if normalised by some metric that allows for the creation of a common basis.

There are two methods for achieving this creation of a common basis. The first requires that the CED of each system is normalised by the rated capacity of the power station (GW), thus providing an indicator of the capital and running energy requirements of the power station per the installed capacity that it provides to the electricity grid it is connected to. The second method involves normalising the CED by the energy output supplied by the power station (GWh). This second method then provides a ratio of energy inputs to the energy supply system divided by its useful output to the wider system. It is argued in this work that the first method (metric based on rated capacity) is of little value even if the systems under consideration have similar operating characteristics (i.e. similar load/capacity factors, operational lifetimes, etc.) but is meaningless when trying to compare systems with widely divergent operational modes. Such is the case in a comparison between an intermittent energy source (wind) and a source that is required to have a steady energy output (nuclear power that is effectively required to operate in “baseload” for the reason outline in Section 4.2). As such, in order to provide an accurate basis for comparison, the CED of the three different power stations (nuclear, onshore and offshore wind) has been normalised by their respective lifetime electricity output to end-use (i.e. the values quoted include transmission and distribution losses). Given the electricity outputs for nuclear (485,802 GWh_e), onshore wind (20,662 GWh_e) and offshore wind (70,337 GWh_e), the normalised CED is displayed in the figure below (in the form of $MJ_{prim.}$ / kWh_e) .

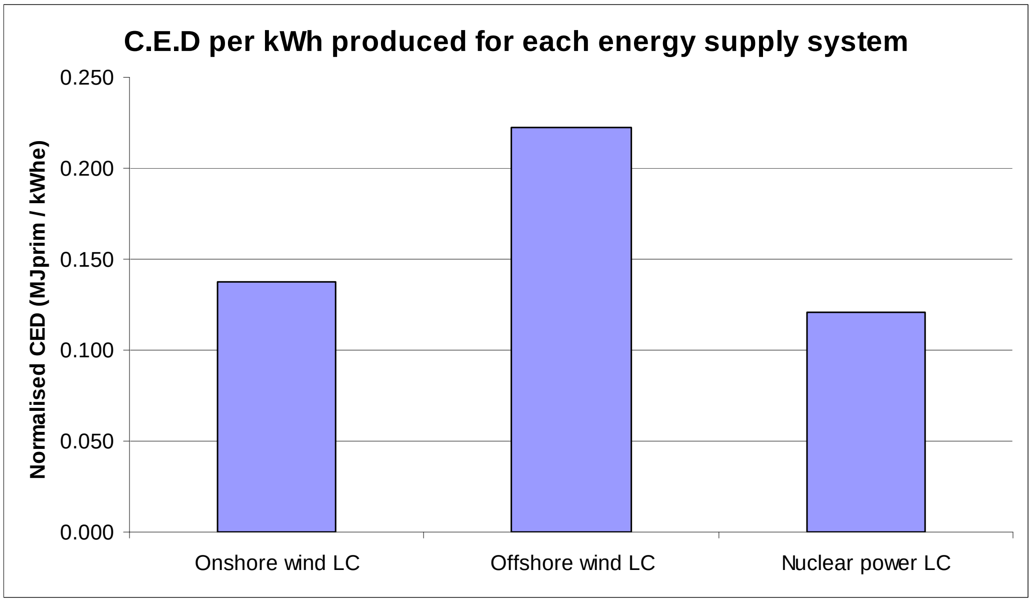

Figure 7.8 Cumulative Energy Demand normalised by power plant electricity output

From the above figure it can be seen that the nuclear fuel cycle has the lowest energy requirements (0.121 $MJ_{prim.}$/ kWh_e), closely followed by the onshore wind farm installation (0.137 $MJ_{prim.}$/ kWh_e) and finally offshore wind (0.222 $MJ_{prim.}$/ kWh_e), which is almost double that of nuclear power. As a first instance, this would seem to indicate that the nuclear life cycle represents a better use of energy resources, compared to wind power in its two forms (on- and offshore) investigated here.

7.2.2 Energy gain ratios and the energetic payback period

As described in Chapter 3 on the Methodology, both the Energy Gain Ratio (EGR) as well as the Energy Payback Period (EPP) are commonly used metrics in the energetic analysis of energy supply systems and have counterparts in economic analysis. The EGR can be generally defined as a parameter that describes how much more energy is provided by a system, compared to the energy inputs required to generate the energy from this system, while the EPP describes the amount of time required for an energy supply system to pay back the energy that was inputted into it. The two parameters are closely related as a system with a high EGR will usually have a shorter EPP than a system with a lower EGR.

An important factor affecting the calculation of both metrics is the valuation of the energy inputs and outputs to the system under investigation. At the most aggregated level of investigation (and the most relevant for this work), the problem can be resolved into a question of how to compare the electrical output of power systems with the thermal energy equivalents that were used as inputs to the said systems. Although it is claimed based on a variety of criteria (thermodynamic quality, price and social utility amongst others), that energy in the form of electricity is more valuable than thermal energy, at the same time electrical supply can also be graduated into different "value streams", depending on *when* and *how* it was generated. A prime example of this graduation is the distinction usually made between baseload or peak load electricity, but also whether the electricity was generated from renewable or conventional energy systems. (Leach 1975a).

The solution to this problem that is adopted in this research is the definition of two different EGRs, as well as two separate EPPs. The exact definitions have been described already in the chapter on the methodological background of the work (Chapter 3), but a brief explanation is also provided here. In the definition of the first Energy Gain Ratio (EGR1) as well as the first Energy Payback Period (EPP1), electrical outputs and thermal inputs are treated as equivalent so the ratios provide a simple division of energy supplies, irrespective of their "value". The second approach, used in the definitions of EGR2 and subsequently EPP2, attempts to attribute a thermal energy equivalent to the electrical outputs. Historically two approaches have been adopted by energy analysts in order to address this issue; the first was used extensively in the early stages of Energy Analysis, as can be seen in the works of (Chapman 1974b) and subsequent editions such as (Leach 1975a) and (Herendeen 1988). This approach supports the view that electricity may have a unique thermodynamic value but the thermodynamic potential actually extracted depends entirely on its end-use application. This then requires detailed knowledge of the end-uses of all the electricity supplied from the energy supply system. However, these end-uses are highly variable, both temporally and geographically, as well as being very difficult to define in the first place. As such, this method requires general assumptions to be made that may or may not reflect reality. The second approach, which has been utilised more recently by (IAEA 1994), defines the value of electricity in thermal terms based on an "opportunity cost". Thus it is assumed that the electricity is equivalent in value to the thermal inputs that would have been required in an alternative (thermal) energy supply system to produce the same amount of electricity. This alternative supply system is usually taken to be a conventional coal-fired station or the total electricity generation mix for the National Grid. Hence, the "opportunity cost" is usually defined by the electricity generation efficiency of an alternative energy system. The problem with this method is the ambiguity of what exactly constitutes the "opportunity cost" of the electricity, as well as the fact that the *lifecycle generation efficiency* of an alternative energy supply system is a more appropriate conversion factor than just the thermal efficiency of that alternative energy supply system, as the former is more representative of the true conversion efficiencies of primary inputs to useful outputs.

Ideally, a factor that incorporates both end-use and "generation opportunity cost" considerations would be the best solution. However it must be noted that there is a clear difference in the boundary conditions associated with each definition. The utilization of an end-use based approach requires that the boundary conditions of the energy supply system extend beyond the delivery of the product (i.e. electricity) to the user. This however is beyond the scope of the current research as it has been assumed that the boundary conditions of the modeling only extend as far as end-user (i.e. they do not include the use of the electricity at the point of supply). A further complication with using the end-use to define, in effect, the value of electricity is that the practical problems associated with such a definition make the utilisation of this approach too hard to implement within the scope of this research project. As a result of the aforementioned considerations, the electrical outputs in this research have been assigned a value based on the “opportunity cost” of the generation method being used. This opportunity cost has been defined on a *lifecycle* basis, unlike most other work in the field, as it was felt that only thus could the full impacts of the alternative system (and therefore the true value of the opportunity cost) be included. The alternative system in this research has been taken as the U.K.’s average electricity generation mix efficiency using information provided by the Department of Trade and Industry (DTI 2008). Using the information supplied therein and the primary energy inputs provided in the Ecoinvent database for each electricity generating technology (e.g. coal-fired, gas-fired, wind power etc), the primary energy equivalents for 1kWh of electricity were calculated. This is effect represented the “opportunity cost” of the electricity from wind power. Thus, it was calculated that the “opportunity cost” had a lifecycle generation efficiency of 35.02%, which has been used in the calculation of EGR2 and EPP2. A final important caveat in the use of the “opportunity cost” is that it has only been applied to the systems based on renewable energy sources (so in this case the onshore and offshore wind farm) for the reason outlined in Chapter 3, and hence the second Energy Gain Ration (EGR2) and Energy Payback Period (EPP2) are only calculated for the wind farms and not the nuclear power plant in the following sections .

7.2.2.1 Energy Gain Ratios for wind power and nuclear power

Based on the results of the modeling, the Energy Gain Ratios (both EGR1 and 2) for the onshore, offshore and nuclear power systems are displayed in the following table:

	Onshore wind	Offshore Wind	Nuclear
Energy Gain Ratio 1	26.2	16.2	29.8
Energy Gain Ratio 2	74.9	46.2	n/a

Table 7.1 Energy Gain Ratios for wind and nuclear life cycles

From the results displayed in the above table, it can be seen that the nuclear power fuel cycle has the highest ratio of output energy to input energy requirements, using the simple Energy Gain Ratio (EGR1). The lowest ratio is exhibited by the offshore wind farm, which has an EGR1 approximately half that of nuclear power. Onshore wind of the other hand, is roughly 40% higher than that of the offshore wind farm and close to the value for nuclear power.

The direct comparison of the values for onshore and offshore wind indicate that although the offshore wind farm has a greater electrical output, the large energy inputs required to create and maintain it, mean that it performs less effectively than its onshore counterpart. This fact is further highlighted by the fact that both wind farms are assumed to have similar capacity factors. This conclusion has to be caveated by the fact that it could be said that the onshore wind farm is in a location of relatively high wind speed resource, whereas the offshore wind farm conversely does not exhibit capacity factors as high (~40%) as those claimed in other reports on offshore wind. As such, in order to make the results of this research more widely applicable, there is a need to investigate the effect that a lower or higher wind speed regime (and the resulting lower or higher electrical output) would have on the lifecycle indicators. The effect that the electrical output (which in turn is connected to the capacity factor) has on the EGR is investigated in the parametric analysis described in following sections.

When combining the above information with the CED results described in the previous section, some interesting results arise. Given the fact that the nuclear fuel cycle has a significantly higher CED than either on- or offshore wind, it still demonstrates a higher Energy Gain Ratio (EGR1) than either other technology. Thus the conclusion can be drawn that the nuclear energy supply system actually represents a more efficient converter of primary energy inputs. This of course has to be contrasted with the fact the wind power cycle does not consume any fuel during operation, since it is assumed that the energy in the wind is renewable and effectively provided for free. In order to illustrate this fundamental difference in the working principles of the two lifecycles, the second definition of the EGR comes into play.

With regards to the second method of defining an Energy Gain Ratio, it can be seen that when the "opportunity cost" is applied to wind power (i.e. when wind power is credited for not depleting non-renewable fuel sources), the individual EGRs of the wind power cycle (represented by EGR2) surpass the EGR for nuclear power (which is still only calculated in the form of EGR1). In this case the Energy Gain Ratio for onshore wind becomes almost double that of the nuclear power fuel cycle. This major difference highlights the importance of a clear statement of the assumptions used in the definition of the energy gain ratios, while it also helps to account for the wide range of seemingly contradictory results exhibited in other works on the subject.

A final comment that can be made from the results so far, relates to the influence that the operational lifetimes have on the EGR. As the definition of the EGR takes into account the energy inputs and outputs over the lifetime of operation, the EGRs of the nuclear and wind power lifecycles will behave differently to changes in the lifetime of operation. Thus the nuclear cycle which requires continuous inputs in the form of nuclear fuel will continue to have an EGR that increases less sharply that that of the wind power fuel cycle's EGR, since the wind power cycle's operational inputs are not proportionally as large. Inversely, a reduction in operation lifetimes of wind farms has a detrimental effect on their EGR, whereas the equivalent effect is not clearly correlated in the case of the nuclear EGR. The reason for this, as previously indicated, is the need for fuel input in the case of the nuclear cycle as well as the ratio of up-front capital costs (in energy costs) compared to the running costs (again in the energetic sense). Thus it can be stated that as the wind power cycle is energy capital intensive but with almost non-existent running *energy* costs, its EGR is almost completely dependent on the assumed years of operation (longer operation leads to cumulatively higher output without further significant energy inputs). Conversely the nuclear power lifecycle's EGR is more strongly dependent on operational inputs throughout its operation since there is always the expenditure associated with providing the fuel for the lifecycle operation. In summary, although more susceptible to fluctuation in operational life, once the initial energy capital has been paid off the EGRs of renewable energy systems will increase more rapidly (within certain limits) than the nuclear power EGR.

In the contrast of two systems, one operating on a non-renewable fuel and the other using a renewable fuel source, it is vitally important to include other metrics to help define the differences in energy output and lifecycle efficiency. A parameter that can assist in this task is the Energy Payback Period.

7.2.2.2 Energy Payback Periods for wind power and nuclear power

	Onshore wind	Offshore Wind	Nuclear
Energy Payback Period 1 (years)	0.95	1.54	2.01
Energy Payback Period 2 (years)	0.33	0.54	n/a

Table 7.2 Energy Payback Periods for the different energy supply systems

Table 7.2 shows the energy payback periods of the different technologies under consideration. As can be seen from the results above, onshore wind repays the quickest with a period of slightly less than a year, followed by offshore wind at approximately 19 months and finally nuclear at just under 25 months. Using the “opportunity cost” convention however lowers the payback ratios of both onshore and offshore wind to approximately 4 months and 7 months respectively.

It is interesting to note here that despite the fact that the nuclear power life cycle has the largest EGR it now exhibits the highest EPP (based on either the simple or “opportunity cost” definition) of the three options. This result demonstrates one of the shortcomings of the definition of the EGR as previously stated, namely that it is dependent on the time during which the energy supply system produces the energy output, i.e. the operational lifetime of the power plant. In effect, the EPP is the inverse of the EGR multiplied by the lifetime of the power plant. As a result, the longer a power plant operates, the higher its EGR, but at the same time its EPP will also increase. Thus the overall effect of an increase in operational lifetime correlates both to the EGR as well as the EPP, but the level of correlation is proportional to the influence of the operational inputs to the lifecycle. Thus the effect on the EPP is less pronounced for the wind power cycle, since the influence from the continuous operational inputs is relatively low. This means that the EPP should be used in conjunction with the EGR, as it provides a better indication of an energy supply system’s energetic utilisation.

A further point of note regarding the high EPP for nuclear power concerns the nature of the fuel cycle. As was seen in the section discussing the CED of this fuel cycle, almost 15% of the energy requirements materialise once the station stops producing electricity. In the case of the renewables, with the exception of the upfront capital costs associated with producing the power plant, there is no connection between the operating requirements and the energy output of the system. On the other hand the nuclear fuel cycle has significant capital energy requirements as well energy expenditures at the end of the operating cycle. As such, the energy requirements are not directly correlated to the energy outputs of the station, inasmuch as the energy expenditures for the fuel cycle can continue to materialise, even once the power station has ceased to provide a useful output. This makes the nuclear fuel cycle particularly sensitive to assumptions regarding the Back End phase. This situation is highlighted in the parametric study later on in the chapter.

7.3 Greenhouse gas emissions

The estimation of the Greenhouse Gases (GHG), which in this study are defined as carbon dioxide and other emissions that have a similar warming effect on the climate, are other main parameters investigated in this research. As stated in previous sections, the need to reduce GHGs has been one of the main drivers in the adoption of energy systems that are deemed to be "low carbon" emitters, among them being of course wind power and nuclear power systems. The ambiguity concerning the exact quantities of emissions related with nuclear and wind generated electricity though has been used by supporters and combatants of both technologies as a tool to promote or discredit one or the other system. As such, it is vital that the issue of GHG emissions is accurately assessed and values for each lifecycle properly calculated.

7.3.1 Total GHG emissions of the nuclear power

Although it is assumed that the nuclear power fuel cycle generates very low levels of GHG emissions during the electricity production stage, it is important to look at the lifecycle stages that precede and follow the electricity production phase. Doing this permits us to properly evaluate all the GHG implications of adopting the nuclear fuel cycle, while at the same time illustrating emissions that aren't immediately obvious when evaluating the electricity produced by nuclear power.

From the modelling of the nuclear fuel cycle, it was estimated that the total life cycle is responsible for the emission of approximately 3,433,000 tonnes CO_{2eq}. Figure 7.9 illustrates the GHG emissions (measured in kg CO_{2eq}) associated with the different stages of the life cycle.

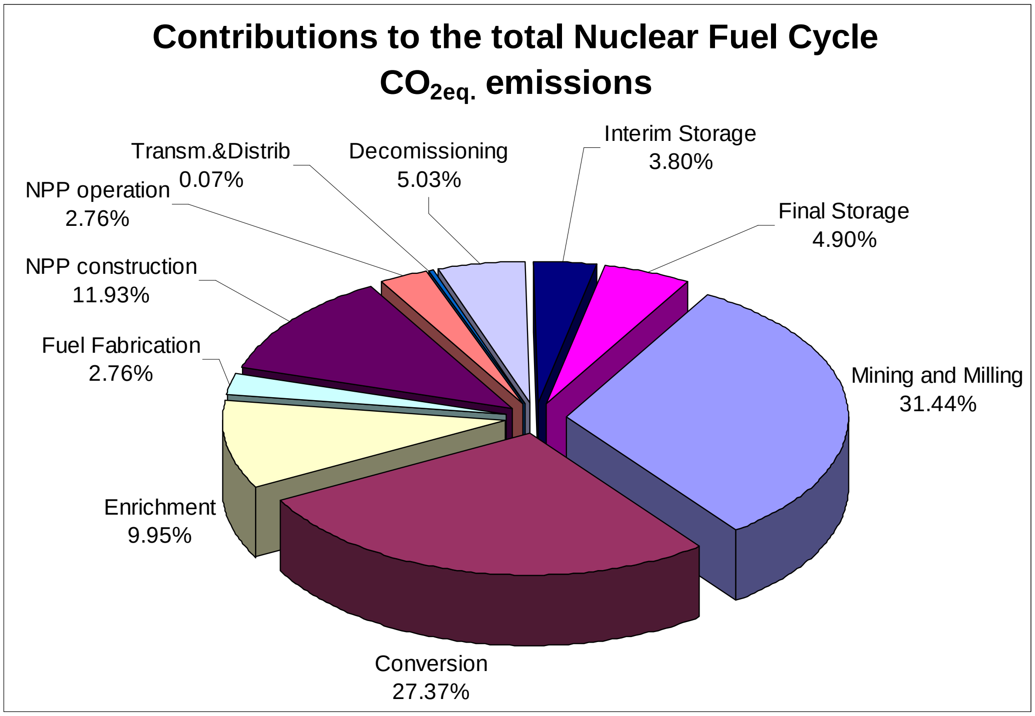

Figure 7.9 GHG emissions associated with the various stages of the nuclear fuel cycle

A comparison with the equivalent figure for the energy requirements of the different stages reveals that there seems to be a significant correlation between the energy and the GHGs for each stage of the life cycle. As a result, the "Front End" is responsible for approximately 72% (approximately 2,455,000 tonnes) of the total life cycle CO_{2eq} emissions. The construction and operation stages are responsible for slightly less than 15% of the total. It is interesting to note that the emissions from construction stage are almost 4 times higher than those associated with the operation stage. However, it must be stressed that there are indirect emissions associated with the actual operation of the nuclear fuel cycle that account for slightly less than 3% of the total (approximately 948,440 tonnes CO_{2eq}). Finally the “Back End” stages in total are worth approximately 13% of the life cycle emissions, which are actually slightly lower than those of the construction and operation stages.

As the Mining and Milling stage comprise the largest percentage of the emissions, it was deemed useful to display a breakdown of its associated emissions by facility. This can be seen in Figure 7.10.

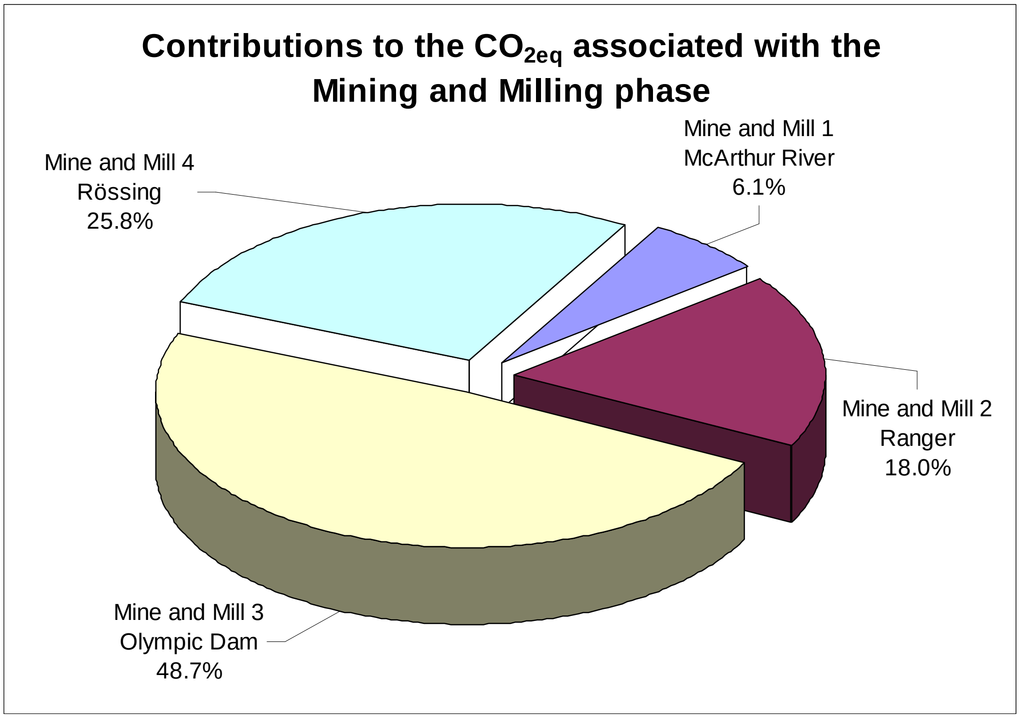

Figure 7.10 Emissions associated with the Mining and Milling Facilities

As in the case of the overall emissions, there is a correlation between the energy requirements and the emissions associated with the 4 different facilities included in this life cycle stage. A slight departure from the trend can be seen in the case of the McArthur River facility, whose emissions make up a smaller percentage of the total than its energy requirements. A closer examination of the ratio of emissions to energy requirements (given in $kgCO_{2eq}$ /MJ_{prim}) demonstrates that McArthur River does indeed have the lowest emissions associated with its operation, compared to the other mining and milling operations. The results can be seen in Table 7.3 below:

	MCARTHUR RIVER & KEY LAKE	RANGER	OLYMPIC DAM	RÖSSING
Emissions per unit of primary energy ($kgCO_{2eq}$ /MJ_{prim})	0.048	0.077	0.070	0.068

Table 7.3 CO_{2eq} Emissions per energy requirements for the mining and milling stage

As already stated Table 7.3 shows that McArthur River and its associated milling facilities have the lowest emissions per energy use, followed by the Rössing facilities. Olympic Dam and then Ranger then follow. The parameter of GHG emissions per unit of primary energy use is complicated to interpret as it is highly dependent on a variety of interconnected factors, which include the energy intensity of the operations (i.e. energy use per unit mass of uranium), as well as the nature of the fuels that are being used to supply the energy. Given what is known about the facilities, it can be said that McArthur River's result can be traced back to the high ore grade which lowers the energy intensity of the facility, while Rössing, although powered completely by electricity generated by the Namibian Grid (with all the associated transmission and generation losses), benefits from the high percentage of low carbon power stations (namely hydro) that generate the electricity. This, combined with the low energy intensity of the mining operations there, means that the low ore grade are, in effect, counterbalanced. Olympic Dam on the other hand, is affected by the high percentage of coal-fired generation on the Australian Grid, as well as the very low ore grade. The reasons for the high value for the Ranger facilities are not completely obvious, as it does not have the lowest ore grade or the highest energy intensity. However, it does meet all its energy demands through the use of onsite diesel powered generation. As such, it is believed that the result is merely an effect of the interplay between all parameters that influence this metric.

7.3.2 Total GHGs of the wind power fuel cycle

As with the nuclear power, the wind power fuel cycle is assumed to have negligible GHG emissions associated with its operational phase, while there are concerns that if considered over the fuel life cycle, wind power have can relative high emissions. As previously, onshore and offshore wind power are treated separately.

Onshore Wind

The correlation between energy requirements and emissions observed in nuclear power fuel cycle holds true also for onshore (and offshore) wind. The breakdown per life cycle stage can be seen in Figure 7.11 that follows. As such, the wind farm manufacturing and construction phases have the highest percentage of associated emissions (72.4%), which results in the emission of approximately 165,000 tonnes CO_{2eq}. The next most influential phase is that of the wind farm operation, which accounts for approximately 23%. Finally, wind farm decommissioning and disposal only accounts for 3% of the total, for the reasons stated previously in the section on the CED.

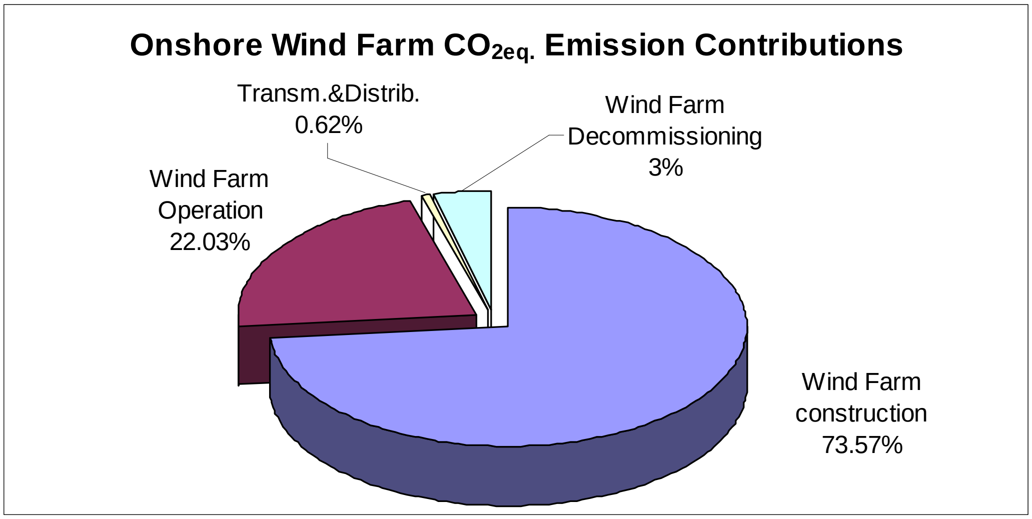

Figure 7.11 Emission contributions from the onshore wind farm life cycle

A closer examination of the "Wind Farm Construction" phase reveals that over 97% of the emissions are associated with the manufacturing and assembly of the wind turbines themselves, with the rest of the emission (<3%) attributable to the building of the wind farm. As the wind turbine represents the largest proportion of the emissions associated with this phase, a breakdown of the associated emissions is displayed diagrammatically in Figure 7.12.

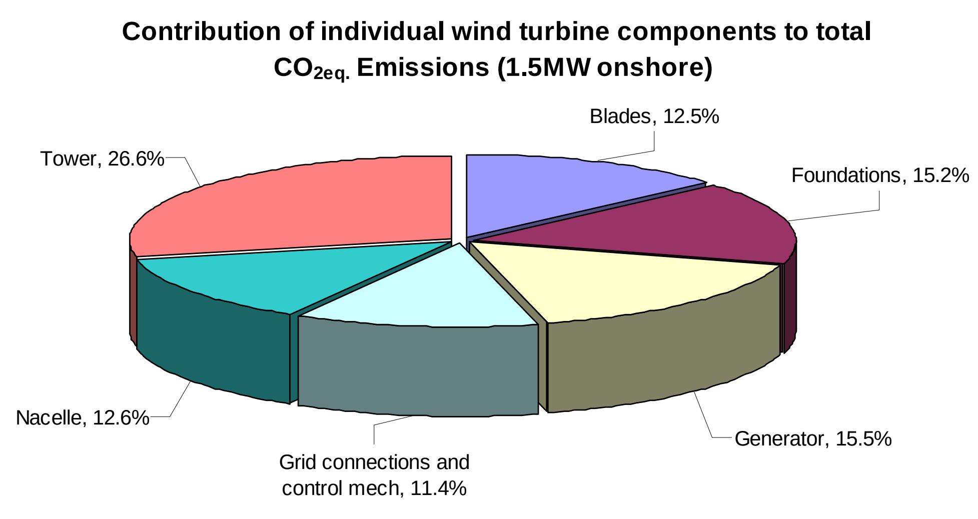

Figure 7.12 Breakdown of emissions associated with a 1.5MW turbine

The tower unit, as also in the energy breakdown displayed in Figure 7.4 previously, represents the largest fraction at approximately 27%, while the Foundations and the Generator are the second most important contributors to the life cycle emissions total. These results can be attributed to the concrete required to make the foundations, which is a carbon intensive material (European Commission 2001) and the large amounts of metals associated with the manufacture of the generator set.

Offshore wind

The offshore wind farm was estimated to be responsible for the emission of 857,000 tonnes CO_{2eq}, over a whole life cycle basis. Figure 7.13 that follows shows the typical breakdown of emissions over the life cycle. When compared to the equivalent figure for the onshore wind farm (Figure 7.11), it is interesting to note that the "wind farm construction" phase accounts for a larger percentage of the emissions in the offshore wind farm life cycle.

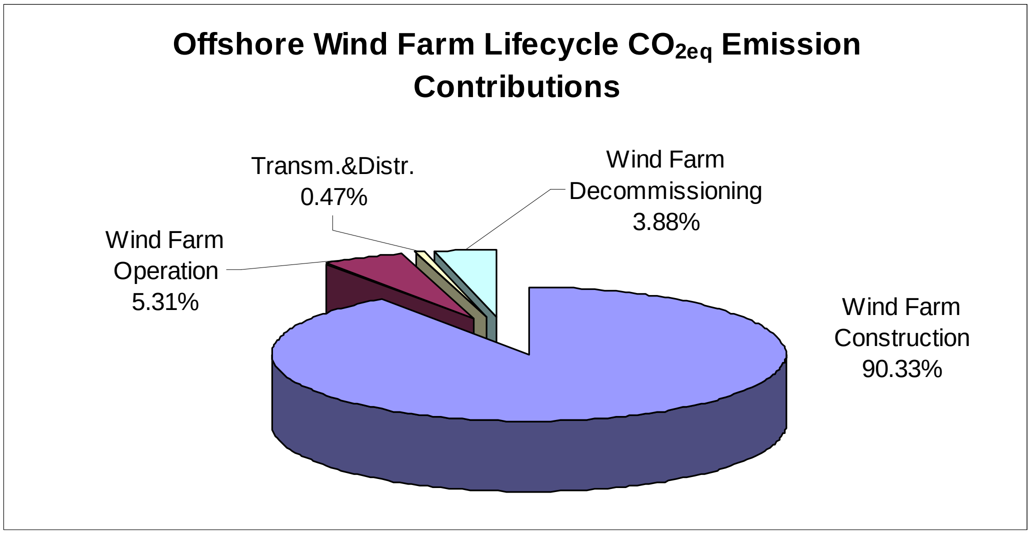

Figure 7.13 Offshore wind farm life cycle emission breakdown

This can be attributed to the large number of wind turbines used in the project and the fact that due to the higher power rating (3.6 and 5MW compared to 1.5MW for the onshore farm), the material requirements are also much larger. A breakdown both the 3.6MW and 5MW turbines' emissions can be seen in Figure 7.14 below:

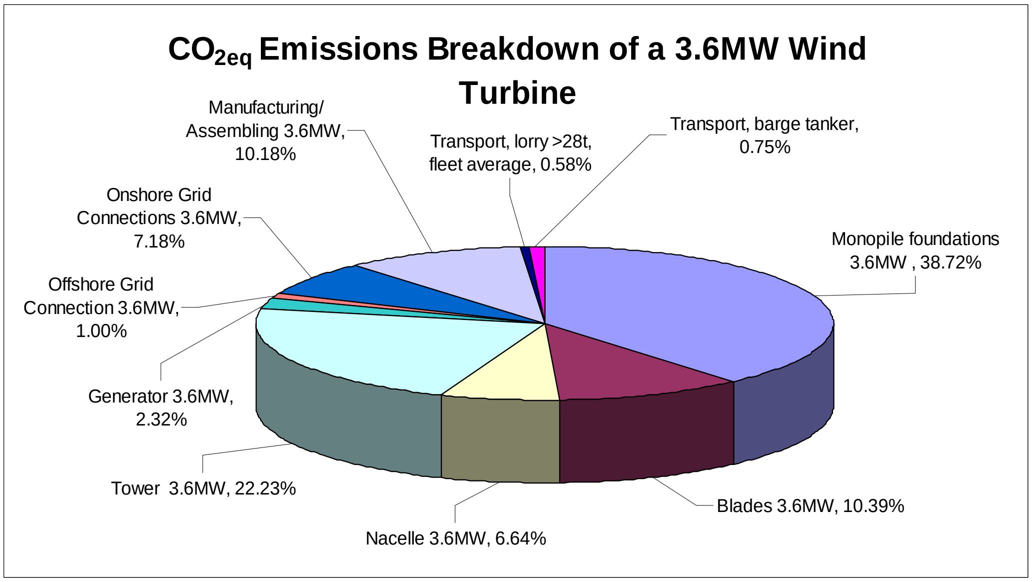

Figure 7.14 Breakdown of emissions associated with a 3.6MW turbine

As can be seen in the above figure the monopile foundations and the tower unit, which are both heavily reliant on steel, have the highest fraction of associated emissions.

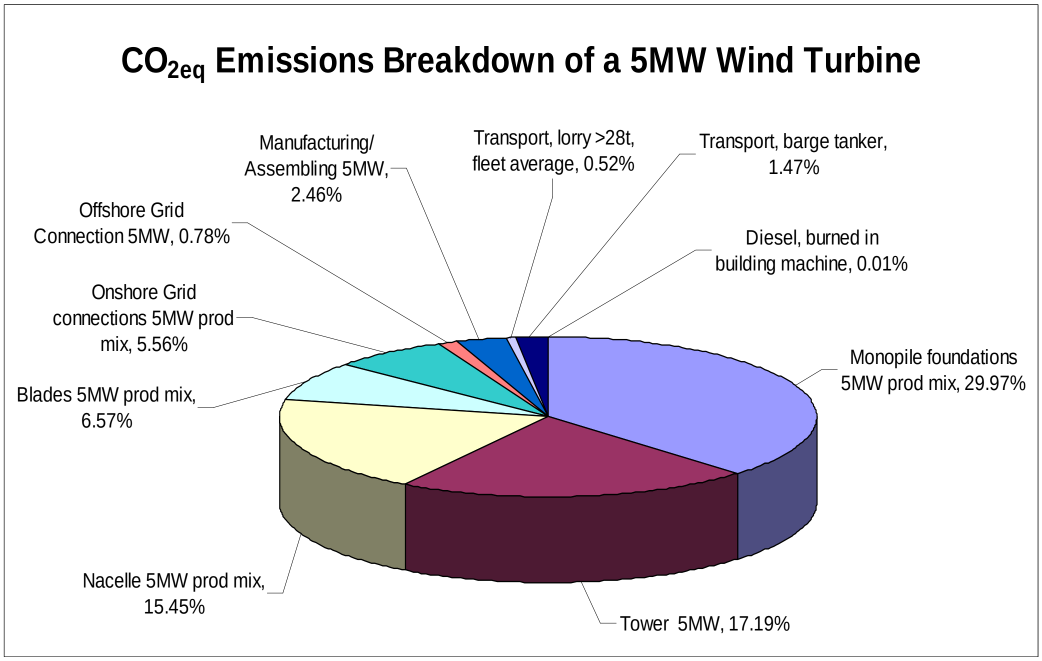

Figure 7.15 Breakdown of emissions associated with a 5MW turbine

A similar picture can be seen in the emission distribution for the 5 MW turbine. Once again the foundations and the tower contribute the most, while for this turbine the nacelle section makes up approximately 15%. This originally appears to be a relative high percentage, especially compared to the 3.6 MW breakdown. However it needs to be remembered that in the modelling of the 5 MW turbine, the nacelle includes the generator, whereas for the 3.6 MW turbine they are modelled as separate components.

7.3.3 Normalised emissions from nuclear and wind power life cycles

The total quantity of emissions associated with the life cycle of any energy supply system is a useful metric in the study of the impact that its adoption might have on the climate. However, in order for the comparison of different systems to be meaningful, it is necessary to normalise the total quantities by their estimated electrical outputs. This then provides a common basis from which to compare the performance of each system. As such the total emissions calculated in the previous sections are divided by the electrical outputs of each energy supply system, which was estimated in Chapter 4. The results of this normalisation are shown in Table 7.4 and represent the estimates for the baseline scenarios used in this research.

	UNIT	NUCLEAR POWER	ONSHORE WIND POWER	OFFSHORE WIND POWER
GHG emissions per unit electrical output	gCO_{2eq} /kWh	**7.6**	**8.6**	**13.1**

Table 7.4 Normalised GHG emissions from the different life cycles

The above table displays carbon dioxide equivalent emissions per unit of electrical output for the *whole* lifecycle, of each energy supply system under consideration. From the tabulated results it can be clearly seen that, for the baseline assumptions adopted for each system, nuclear power has the lowest life cycle emissions. The next lowest emissions are associated with onshore wind, while offshore wind exhibits the highest life cycle emissions of the three systems. It is important to stress that these estimates represent only the results for the baseline assumptions in each model. To provide a more complete picture of the range of results that could be expected, a parametric investigation of the parameters affecting each energy supply system is undertaken.

For each energy supply system, it is possible to display the normalised emissions of each life cycle stage. This allows the identification of the most carbon intensive stage of the life cycle which could in turn help focus activities for reducing the associated emissions. The normalised life cycle emissions for nuclear and onshore and offshore wind, per life cycle stage, are shown in Tables 7.5, 7.6 and 7.7. For the nuclear fuel cycle, mining/milling and conversion are the most emission intensive.

Emission per stage	Mining /Milling	Conversion	Enrichment	Fuel Fabrication	NPP Construction	NPP Operation	Transmission & Distribution	De-commissioning	Interim Storage	Final Disposal	**Total**
gCO_2 eq/ kWh	2.39	2.08	0.76	0.21	0.91	0.21	0.01	0.38	0.29	0.37	**7.61**

Table 7.5 Breakdown of normalised nuclear power emissions

For onshore wind power, the following breakdown is observed:

Emission per stage	Wind Farm construction	Wind Farm Operation	Transm.& Distrib.	Wind Farm Decommissioning	**Total**
gCO_2 eq/kWh	6.29	1.88	0.05	0.32	**8.55**

Table 7.6 Breakdown of normalised onshore wind emissions

Finally, offshore wind exhibits the following breakdown of normalised emissions by stage:

Emission per stage	Wind Farm construction	Wind Farm Operation	Transmission & Distribution.	Wind Farm Decommissioning	**Total**
gCO_2 eq/kWh	11.85	0.70	0.06	0.51	**13.11**

Table 7.7 Breakdown of normalised offshore wind CO_{2eq} emissions

7.4 Parametric analysis of Net Energy and GHG emissions

Although the baseline scenarios for each energy supply system demonstrate the results for the metrics of net energy and GHG emissions, for what were deemed to be the most applicable input values, it was felt that a single result did not provide sufficient depth of analysis. As a result, a range of estimates for these output metrics was sought, that would better represent the real-life variations of performance that could be expected by each energy system. These ranges are based on the manipulation of various input parameters to the models, such as operational lifetimes, energy outputs, load/capacity factors and so on. All the variations of the input parameters were based on the likely variations of each as were described in academic literature or based on historical data. Thus by varying the different input parameters within prescribed limits, the likely variations of net energy and GHG emissions were established.

Each energy supply system was investigated separately since they did not all have the same input parameters, and even when these were common, the ranges of values (as indicated in external sources) were not applicable. For each technology, the input parameters that were to be manipulated were first identified, and then a likely range of values (either side of the baseline condition) was established.

7.4.1 Nuclear Power Life Cycle

The nuclear fuel cycle, due to its complexity, is sensitive to the assumptions made about it and hence it is important to stress and evaluate the impact of the different input parameters on the total emissions and energy requirements of the nuclear fuel cycle. As part of the nuclear fuel cycle model, it was decided that a parametric analysis would provide a useful insight into how variations in certain parameters could affect the total environmental impacts of the model. Based on past studies (ISA 2006; Jan Willem Storm van Leeuwen & Philip Smith 2005) and the results of the model, it was decided that the main parameters that should be investigated were the following:

Load Factor (%): The value in the base-line scenario (85%) is based on the lifetime estimates for the Sizewell B, the U.K.'s only operating PWR, as detailed in IAEA's Reactor Information database (IAEA 2008). Similar values were also used by NIREX in their report on the AP1000 reactor (Vande Putte D. & NIREX UK LTD 2004). Historically however, load factors for the U.K.'s fleet of nuclear reactors have been lower. Difference in reactor types notwithstanding, the average load factor since 1996 was estimated to be 74% based on work by (Maloney 2003), while for the period 2003-2007, the average load factor was calculated to be 70.2% (DTI 2008). Based on this information, a lower limit of 70% was chosen for the parametric study. Many commentators however, have claimed that the next generation of nuclear power stations will be able to achieve very high load factors (> 90%), as a result of better design characteristics and improved fuel management scenarios. This level of performance has been observed in current NPPs (91% for Sizewell B during 1996 (Meyer & Stokke 1997)), but only for limited time periods and certainly not as a lifetime average.

Operational Lifetime (years): The value of 60 years was used in the original calculations, based on the estimates of Westinghouse Electric Company LLC (British Nuclear Fuel plc & Westinghouse Electric Company LLC 2002). However, most current designs in operation have an estimated operational lifetime of 40 years. This was taken as the lower limit of the variations. On the other end of the scale, through extensions to the design lifetime, as is becoming common now for older designs nearing closure, lifetime extensions might also be granted to Generation III+ designs. In this parametric study an extension of 20 years has been assumed, giving a total operational lifetime of 80 years.

Burn-up (GWd/tU): The design characteristics for the AP1000 specify an average burn-up rate of 48 GWd/tU (Winters & Corletti 2001). This value was varied between 35 and 60 GWd/tU, to simulate a frequent and infrequent core reload respectively, outlined in the various papers on core management and the AP1000 design (Westinghouse Electric Company LLC 2007; Schulz 2006; Cummins, Wright, & Schulz 2000).

Enrichment Method (%): The baseline method was based on enrichment based on 100% centrifuge. This parameter was varied between the use of 100% diffusion enrichment processes, and a mix of 70% centrifuge and 30% diffusion processes, based on the assumptions outlined in (ISA 2006).

Product Enrichment (%): As stated earlier, many of the parameters of the nuclear reactor were based on the Westinghouse AP1000. Specifically, the AP1000 specifications designated the required enrichment level at 4.95% (Energetics Incorporated 2005). This value was varied between 3.5% - 6.5%, to establish the impact on the lifecycle.

Tails Assay (%): The tails assay will vary depending on the trade-off between the relative price of uranium ore and electricity. Two extremes were tested, namely the case of cheap uranium (0.4% tails) and that of expensive uranium with relation to the energy price for enrichment (0.2% tails).

Ore grade (%): The baseline case is focused in the use of four different mines, with different ore grades, providing the uranium oxide required for the reactor's operation. As such, to test the sensitivity of the model to the ore grade, each mine was allocated 100% of the production requirements, providing the impacts for the different ore grades (0.03%, 0.04% by-product 0.3% and 17.3%).

Operational Lifetime of Back End facilities (years): In the baseline scenario, it was assumed that the operational lifetime of the interim storage was 55 years, based on (Dones R. 20087), while the operational lifetime (i.e. the period over which the waste is actively monitored) of the final repository is 50 years (Ernst & Young LLP 2006). To get a range of values for this parameter, both the interim and the final storage were modified. In an extreme case, where the "Back End" of the nuclear fuel cycle had been completely integrated and streamlined, it is hoped that significantly lower residing times in interim storage could be achieved. This scenario is represented by a interim lifetime of 10 years. On the other end of the scale, an operational lifetime of 500 years has been investigated for the final repository, reflecting the concern that nuclear waste will not be able to be "buried and forgotten". This is represented by adjusting the operational lifetime of the said facility to 500 years (a tenfold increase on the baseline). Finally, a combination of the two assumptions (i.e. 10 years in interim and 500 years in final storage) is also investigated.

Depleted Uranium management (years): An issue not investigated in the baseline scenario is that of the management of depleted uranium waste (mainly tails from the enrichment of UF_6). This stage is based on the assumptions outlined in (Jan Willem Storm van Leeuwen & Philip Smith 2005) and the follow up in (Storm van Leeuwen 2007). According to this work, it is assumed that the UF_6 tails will need to be re-converted to U_3O_8 for final storage. This approach however is not common in studies in the area of nuclear fuel life cycle and as such was not included in the baseline scenario. For the sake of completeness however, the effect of this addition to the life cycle is investigated in the parametric study. The process is modelled using the generic conversion plant entry from the Ecoinvent database and then assuming sub-surface burial.

7.4.1.1 Results of the parametric analysis for nuclear power

The ranges for net energy and GHG emission metrics can be seen in Table 7.8. below, while the analytical outline of the effect that each parameter has on the results of the parametric study can be seen overleaf in Table 7.9.

GHG emissions	gCO_{2eq}/kWh_e	5.74	—	10.24
Energy Gain Ratio (EGR1)		4.51	—	37.83
Energy Payback Period (EPP1)	years	1.46	—	13.30

Table 7.8 Ranges of values for select parameters describing the nuclear power life cycle

As can be clearly seen, the difference between the lowest and highest estimate for GHG emission is almost 100%, while the highest value for EGR1 is almost 8 times higher than lowest estimate. Finally, the largest range of values can be seen in the calculation of the EPP1, where the lowest values is almost 9 times lower than the other extreme of the range.

A more detailed examination of Table 7.9 (overleaf), reveals which parameters lead to highest and lowest values for each metric. The extremes of GHG emission ranges are attributable to case where low levels of enrichment (3.5% as opposed to 4.95%) are assumed, while the highest values are based on the condition that the final repository will require active monitoring for 500 years. With respect to the Energy Gain Ratio, its highest value was achieved again when the level of enrichment of the product (i.e. the nuclear fuel) was reduced to 3.5%, while the lowest EGR was attributable to the situation where an all-diffusion enrichment method was chosen. This choice also resulted in the longest Energy Payback Period, while the quickest payback period was achieved when the operational lifetime of the nuclear power plant was shortened to 40 years.

Parameter		Value	Variation	EGR1	Sensitivity	GHG emissions	Sensitivity	Payback Time	Sensitivity
	Baseline values			**29.83**		**7.61**		**2.01**	
	Rössing	0.03%	-	28.96	-2.9%	7.84	3.1%	2.07	3.0%
	Olympic Dam	0.04%	-	23.58	-20.9%	9.90	30.1%	2.54	26.5%
Ore Grade (%)	Ranger	0.30%	-	33.31	11.7%	6.95	-8.6%	1.80	-10.4%
	McArthur River	17.30%	-	36.83	23.5%	5.74	-24.5%	1.63	-19.0%
	25/25/25/25 mix		-	29.83	-	7.61	-	2.01	-
	low values	0.25%	-16.7%	31.24	4.7%	7.26	-4.6%	1.92	-4.5%
Tails assay (%)	baseline case	0.30%	-	-	-	-	-	-	-
	high value	0.35%	16.7%	28.08	-5.9%	8.09	6.4%	2.14	6.2%
	low values	3.50%	-29.3%	37.83	26.8%	5.99	-21.3%	1.59	-21.2%
Product Enrichm. (%)	Baseline	4.95%	-	-	-	-	-	-	-
	high value	6.50%	31.3%	24.30	-18.5%	9.35	22.9%	2.47	22.8%
	low values	all diffusion		4.51	-84.9%	7.36	-3.2%	13.30	561.1%
Enrichm. Method	mid range	70/30 mix		11.12	-62.7%	7.53	-1.0%	5.40	168.3%
	baseline	all centrifuge		29.83	-	7.61	-	2.01	-
	low values	35	-27.1%	23.17	-22.3%	9.77	28.5%	2.59	28.7%
Burn up (GWd/tU)	baseline	48	-	-	-	-	-	-	-
	high value	60	25.0%	35.28	18.3%	6.44	-15.3%	1.70	-15.5%
	low values	70	-17.6%	28.79	-3.5%	7.91	3.9%	2.08	3.6%
Load factor (%)	baseline	85	-	-	-	-	-	-	-
	high value	95	11.8%	30.37	1.8%	7.46	-1.9%	1.98	-1.8%
	low values	40	-33.3%	27.44	-8.0%	8.33	9.4%	1.46	-27.5%
Op. Lifetime (yrs)	baseline	60	-	-	-	-	-	-	-
	high value	80	33.3%	31.18	4.5%	7.25	-4.7%	2.57	27.5%
	Interim 10 years	-	-	30.42	2.0%	7.47	-1.8%	1.97	-2.0%
Back End	Repository 500 yr	-	-	21.75	-27.1%	10.24	34.6%	2.76	37.1%
	Inter.+Rep 10/500	-	-	22.06	-26.0%	10.10	32.8%	2.72	35.2%
Depleted uranium	-	-	-	23.58	-20.9%	9.53	25.2%	2.54	26.5%

Table 7.9 Results for parametric analysis of nuclear power

The fact that a shortened operational lifetime results in a faster EPP may seem counterintuitive at first but after closer evaluation appears possible. As the EPP is defined as the total amount of energy inputs over the lifetime of the lifecyle divided by the yearly energy output of the system, it can be argued that a shorter operational cycle will therefore require less energy inputs (in the form of energy to process the fuel and deal with the waste) that would a longer period of operation. The yearly energy output of the system however will remain the same in both cases. As a result, the EPP will be reduced as the numerator also reduces. Another counterintuitive result can be found in the variations of the ore supply by choosing different mines. From this analysis, as can be seen in Table 7.9, if the nuclear power plant was supplied throughout its lifetime by ore from Rössing (which is the lowest grade ore of the four mines investigated), the effect on the three indicators investigated here (EGR, GHG emissions and EPP) is marginal. Another important point to note is the similar results between supplying ore from McArthur River and from Ranger. Although the two mines have vastly different ore grades, their results are quite similar and in the case of EGR and EPP, Ranger actually produced better results despite having the lower ore grade. These counterintuitive results are believed to be the result of data ambiguities. The Ranger mine and mill is modelled with data provided directly from the company's environmental reports. McArthur River however, has been modelled by adapting the data from a generic North American uranium mine, as provided in the Ecoinvent database. This is sure to generate some discrepancies given the unique nature of the mine (i.e the richest uranium ore reserves to date). A closer examination of the mine and mill's modelling module also reveals further information. Although the milling facility is modelled using site-specific data, it has to be noted that the McArthur ore is so rich, that it is actually diluted in order for it to be passed on to the conversion facilities. This fact however, is also not properly represented in the energy and emissions attributions, so a correction has been applied to take this fact into account.

A final parameter investigated in the parametric analysis of the nuclear power life cycle was the effect that the quantities of construction materials used had on the metrics of Energy Gain Ratio, GHG emissions and energy payback period. As described in previous chapters, the modelling of the nuclear power plant was based on the data provided in (DoE 2005). However, one of the most complete datasets was found in (Bryan & Dudley 1974), with the drawback that the data was accumulated for a late 1960s/early 1970s reactor design and was therefore judged non-representative of current innovations. However, for the sake of completeness the original 1971 data was used in the parametric study to investigate the effect that it would have on the lifetime metrics discussed above. The results of substituting the bill of materials for older reactor data can be seen in Table 7.10 below:

Parameter	**EGR1**	Sensitivity	**GHG emissions**	Sensitivity	**Payback Time**	Sensitivity
Baseline	**29.83**	-	**7.61**	-	**2.01**	-
1971 data	*27.86*	*-6.6%*	*8.02*	*5.39%*	*2.15*	*6.97%*

Table 7.10 Parametric results for 1971 bill of materials

As previously stated, the effect that the 1971 data has on the fuel cycle was not included in the ranges given for the parametric results, as the use of these quantities was not deemed credible, within the context of this work. However it is interesting to note that the effect of the use of “1971 bill of materials” is marginal in almost all cases for the three parameters cited above.

7.4.1.2 Results from previous studies for nuclear power

The following table (Table 7.11) provides a summary of results from previous relevant works in the field of the Energy and GHG emission assessements. These results are provided to allow the comparison of the results of this study with other studies, thus allowing them to be put in the correct context and highlight similarities and discrepancies. The works shown in Table 7.11 have already been discussed in Chapter 2, so no further commentary has been provided here.

Previous Work	**Energy Gain Ratio**	**Energy Payback Period (yrs)**	**Emissions (gCO_2 /kWh)**	**Comment / Reference**	
Chapman, 1974	8-19	n/a	-		(Chapman 1974b)
Chapman/Mortimer, 1974	12.9±3	1.93±0.3	-	0.3% &3.35% enr	(Chapman & Mortimer 1974)
Wright / Syrett, 1975		1.7-2	-		(Wright & Syrett John 1975)
Oak Ridge Associated Universities, Inc. 1975	4.6/15.35	-	-	R1/R3 for Ore grade 0.176%	As cited in (IAEA 1994)
ERDA, 1976	3.83	-	-	EGR1	As cited in (IAEA 1994)
Inst. Policy & Science, 1977	16.18 / 46.11	-	-	EGR1/2	As cited in (IAEA 1994)
Fritsche, Rausch, Simon, 1989	-	-	16.7		As cited in (IAEA 1994)
Uchiyama, Y. 1991	17.4	0.07	-	EGR2	As cited in (IAEA 1994)
van de Vate, 1997	-	-	9		(van de Vate 1997)
White et al 1998	25	-	10		(White 1998)
Kivisto 2000	59	-	10-26	EGR2	as quoted in (WNA 2005a)
Rashad 2000	17.4	-	10-70	CO_2 eq.	(Rashad & Hammad 2000)
Gagnon et all, 2001	-	-	15		(Gagnon, Belanger, & Uchiyama 2002)
Vattenfall Ringhals EPD, 2004	-	-	3.48	CO_2 eq.	(Vattenfall AB 2004b)
Vattenfall Forsmark EPD, 2004	-	-	3.1		(Vattenfall AB Generation Nordic Countries. 2004)
Dones 2005	-	-	5-12	CO_2 eq.	(Dones, Heck, Faist Emmenegger, & Jungbluth 2005)
Hondo, 2005	-	-	24.2		(Hondo 2005)
British Energy Torness EPD, 2005	-	-	5.05		(AEA Technology & British Energy 2005)
WNA, 2005	58	-	-	EGR2	(WNA 2005a)
SDC Paper 2 2006	-	-	16		(Sustainable Development Commission 2006b)
Fthenakis 2007	-	-	16-22	CO_2 eq.	(Fthenakis & Kim 2007)
Current work	**4.5-37.8**	**1.5-13.3**	**5.7-10.2**		

Table 7.11 Summary of previous results for nuclear power

7.4.2 Wind Power Life Cycle

As for the nuclear power life cycle, a parametric analysis was also carried out for the onshore and offshore wind farms. The two studies had many common parameters, but certain parameters specific to offshore wind (i.e. the types of foundations used to secure the wind turbines to the seabed) were also investigated. As such, each wind farm is investigated separately.

7.4.2.1 Onshore wind farm

For the onshore wind farm, 4 parameters were investigated and variations in the wind farm's energy output were modelled, as were changes in the wind farm's operational lifetime. The distance over which the scrap was transported was also varied to study its effect on the lifecycle. Finally, variations in predicted site wind speed were also simulated. The range over which each parameter is investigated is presented and then explained in more detail in the following sections.

Wind Farm Energy Yield: The energy yield of the wind farm was varied 10% either side of the baseline value that was calculated by using U.K. Meteorological Office data. The range of 10% was chosen as this reflected the variations in output observed when different turbine power curves were used in the wind farm energy output estimations. This variation also then gave wind farm capacity values closer to the range prescribed by previous studies (25.7% - 38.6%) on capacity factors for the region and the U.K. in general (DTI & DT 2006; Sinden & Environmental Change Institute 2005).

Operational Lifetime: A variation of 10 years either side of the baseline lifetime (25 years) was chosen as the range for this parameter. This then encompassed the possibility of early decommissioning, as well as the possibility of an extension in the operation of the wind farm. At the time of writing, exceedingly few wind farms have actually been decommissioned and hence very little data exists as to the maximum potential lifetime of a wind farm. Furthermore, due to the nature of the resource, it is becoming apparent that many wind farm owners will prefer to remove current installed turbine designs and re-power the site with more modern and possibly larger wind turbines (thus for all practical purposes, creating a new wind farm), as such time as that becomes financially viable. As such, it is unlikely that wind farm will remain unchanged for long periods after its originally projected operational lifetime (which is also defined by financial factors). Likewise, it is also unlikely that the lifetime will be severely curtailed as this will also impact the viability of the original financial projections. Finally it is important to note that not all the components comprising a wind turbine will have the same operational lifetime. Thus an extension of 10 years of operation, has been assumed to be possible without major overhauls of equipment (maintenance during the original 25 years has already been accounted for).

Disposal Transportation Distance: In order to capture the effects of this parameter it was felt that a range of values should be used to illustrate the contribution of the waste transportation distance. To do this, a variation of 100 km was arbitrarily chosen either side of the baseline value (200km).

Wind speed: The predicted wind speed at the proposed wind farm was varied 15% either side of the baseline value that was calculated from the Meteorological Office reference stations. The range of 15% was chosen as this reflected the variations in the predicted site wind speed depending on the reference station used to calculate the site specific value. It should be noted that windspeed and energy outputs are of course linked, but not with a linear relationship. From equation 4.7 in Chapter 4, the power output is more closely linked to the cube of the windspeed, Thus windspeed variations have a more pronounced effect on the lifecycle, than equivalent variations in power output.

The resulting ranges of values calculated from the parametric study of onshore wind can be seen below, in Table 7.12:

GHG emissions	gCO_{2eq}/kWh_e	6.11	—	14.25
Energy Gain Ratio (EGR1)		15.75	—	36.69
Energy Payback Period (EPP1)	years	0.84	—	1.17

Table 7.12 Ranges of values from parametric study of onshore wind

For the GHG emissions, the upper and lower ranges are both defined by the operational lifetime of the wind farm. By increasing the wind farm’s lifetime by 10 years the emissions per kWh are reduced by approximately 29% while decreasing the wind farm lifetime by an equal amount results in an increase of 67% in the lifecycle emissions per kWh. The Energy Gain Ratio range of values is also affected by the same parameter (i.e. operational lifetime). Finally, the Energy Payback Period is influenced most extremely by the site’s annual predicted wind speed.

The exact variations of the onshore parametric study are shown in Table 7.14 in the Section 7.4.2.3.

7.4.2.2 Offshore Wind Farm

The offshore wind farm’s parametric study used the same format as that of the onshore wind farm described above with the addition of a parameter to vary the type of foundations used to secure the wind farm to the location. A brief description of each varied parameter is given in the following sections

Wind Farm Energy Yield: The energy yield of the wind farm was varied 20% either side of the baseline value, that was calculated using the aggregated wind data provided by (RPS & London Array Ltd 2005). The range of 20% was chosen as this then gave wind farm capacity values (25% - 38%) within the range prescribed by previous studies on capacity factors for the region and the U.K. in general ((DTI & DT 2006; Sinden & Environmental Change Institute 2005)).

Operational Lifetime: As for the onshore wind farm, a variation of 10 years either side of the baseline lifetime (25 years) was chosen as the range for this parameter. Similar issues to those highlighted in the equivalent section for the onshore wind farm are also valid here, so they are not discussed in detail again. It is important to note however that there is even less relevant information for offshore wind farms due to the level of maturity of the sector.

Foundation type: In the Environmental statement of the London Array project (RPS 2005), on which the offshore wind farm is based, it is stated that the type of foundations had not been decided upon; as a result, a monopile foundation was assumed for the baseline scenario, while the other two options (caisson and tripod) were investigated in this parametric study.

Disposal Transportation Distance: In addition to the transportation by sea, an on-land transportation distance of 200 km was assumed in the baseline scenario. Then as in the case of the onshore wind farm, a variation of 100 km was arbitrarily chosen either side of the baseline value (200 km).

The resulting ranges of values calculated from the parametric study of offshore wind can be seen below, in Table 7.14:

GHG emissions	**gCO_{2eq}/kWh_e**	9.37	—	21.85
Energy Gain Ratio (EGR1)		9.73	—	22.59
Energy Payback Period (EPP1)	**years**	1.18	—	1.95

Table 7.13 Ranges of values for parametric study of offshore wind

The upper level of the GHG emissions range is related to the reduction of operational lifetime to 15 years, whereas its lowest value is attributable to an extension of the lifetime of the wind farm to 35 years. The Energy Gain Ratio’s extremes are also most influenced by the operational lifetime, with the longest lifetime giving the highest EGR and vice versa. Finally, the longest Energy Payback Period is attributable to the use of caisson foundations for the wind turbines, while the use of tripod foundations gives the fastest EPP.

The exact variations of the offshore parametric study are shown in Table 7.15 in the Section 7.4.2.3.

7.4.2.3 Summary of results from parametric studies for wind power

Parameter	Comment	Variation	EGR1	Sensitivity	gCO_{2eq}/kWh	Sensitivity	EPP1	Sensitivity
			26.23		**8.55**		**0.95**	
Wind estimations	Low	-20%	23.61	-10.0%	9.51	11.1%	1.06	11.1%
	High	20%	28.85	10.0%	7.78	-9.1%	0.87	-9.1%
Lifetime	15 years	-40%	15.75	-39.9%	14.25	66.6%	0.95	-0.1%
	35 years	40%	36.69	39.9%	6.11	-28.5%	0.95	0.1%
Disposal Distance	100km	-50%	26.47	0.90%	8.48	-0.9%	0.94	-0.9%
	200km							
	300km	50%	26.00	-0.88%	8.63	0.9%	0.96	0.9%
Wind speed variations	Low	-15%	21.34	-18.7%	10.52	22.9%	1.17	22.9%
	Baseline							
	High	15%	29.63	13.0%	7.57	-11.5%	0.84	-11.5%

Table 7.14 Results for parametric analysis of onshore wind power

Parameter	Comment	Variation	EGR1	Sensitivity	gCO_{2eq}/kWh	Sensitivity	EPP1	Sensitivity
			15.74		**13.48**		**1.59**	
Energy output estimate		-20%	12.95	-20.0%	16.39	25.0%	1.93	25.0%
		20%	19.42	20.0%	10.93	-16.7%	1.29	-16.7%
Lifetime	15 years	-40%	9.73	-39.9%	21.85	66.6%	1.54	-0.2%
	35 years	40%	22.59	39.6%	9.37	-28.5%	1.55	0.3%
Foundation Type	caisson		12.80	-20.9%	17.73	35.2%	1.95	26.5%
	monopile							
	tripod		21.15	30.7%	9.89	-24.6%	1.18	-23.5%
Disposal Distance	100km	-50%	16.28	0.60%	13.04	-0.6%	1.54	-0.6%
	200km							
	300km	50%	16.09	-0.59%	13.19	0.6%	1.55	0.6%

Table 7.15 Results for parametric analysis of offshore wind power

7.4.2.4 Results from previous studies for Wind power

Table 7.16 that follows, gives a brief overview of results from previous studies for onshore and offshore wind. As with the summary of the results from previous studies on nuclear power, the works including the in the following table have been be discussed in the Literature review in Chapter 2.

Previous Work	EGR	EPP (yrs)	Emissions (gCO_2/kWh)	Comments / References	
Resource Research Inst. 1983	12	-	-	EGR2	as cited in (WNA 2005a)
Uchiyama 1996	6	-	-	EGR2	as cited in (WNA 2005a)
Kivisto 2000	34	-	-	EGR2	as cited in (WNA 2005a)
Gagnon et al 2002	80	-	-	EGR2	as cited in (WNA 2005a)
Aust. Wind Energy Ass. 2004	50	-	-	EGR2	as cited in (WNA 2005a)
Wiese/Kaltschmitt 1996	50-150	-	13-22		as cited in (Lenzen & Munksgaard 2002)
ExternE 1995	23.8	-	9.1	1 turbine / UK	as cited in (Lenzen & Munksgaard 2002)
Roberts 1980	12.5	-	-	1 turbine / UK	as cited in (Lenzen & Munksgaard 2002)
Proops et al 1996	n/a	-	25	1 turbine / UK	(Proops, Gay, Speck, & Schroder 1996)
Schleisner 2000	30.3	-	9.7	0.5 MW/Denmark	(Schleisner 2000)
Wiese/Kaltschmitt 1996	28.6	-	10	C.f 36.2% / Germany	as cited in (Lenzen & Munksgaard 2002)
Voorspools 2000	30.30	-	9.2	0.6MW / CO_2 equiv.	(Voorspools, Brouwers, & D'haeseleer 2000)
Stelzer et al 1994	14.7	-	8.1	0.5MW	cited in (Lenzen & Munksgaard 2002)
Wagner / Pick 2004	39-64	0.32-0.52	-	1.5MW	(Wagner & Pick 2004)
Rydh et al 2004	62	0.32	11		(Rydh, Jonsson, & Lindahl 2004)
Elsam 2004	n/a	0.65	6.8	EPD for 2 MW	(Vestas Wind Systems A/S & Elsam Engineering A/S 2004)
Vestas 2005	-	0.55	4.64	EPD for 3 MW	(Vestas Wind Systems A/S 2005)
Enel 2004	-	-	16.9 (eq.)	0.66MW w.t.	(Enel SpA 2004)
Current work *-onshore*	**15.6-36.7**	**0.8-1.2**	**6.1-14.3**		
Current work *-offshore*	**9.7-22.6**	**1.2-2.0**	**9.4-21.9**		

Table 7.16 Summary of previous results for Wind power

7.4.3 Summary of results from parametric studies of current work

This section provides a summary of the results found from the previous sections, and specifically a summary of the parametric studies carried out in the immediately preceding sections. The estimates for the two main parameters investigated in this work (Energy Gain Ratio and normalised GHG emissions) are shown in Tables 7.17 and 7.18.

Energy Gain Ratio EGR1	High	Low	**Baseline**	Range
Offshore Wind Farm LC	22.59	9.73	**16.19**	12.86
Onshore Wind Farm LC	36.69	15.75	**26.23**	20.94
Nuclear Powerplant LC	37.83	4.51	**29.83**	33.32

Table 7.17 Summary of results for the energy gain ratios of the three energy supply systems

From the above table it can be seen that nuclear power life cycle demonstrates the largest range of values, when considering the metric of EGR. Both onshore and offshore wind power have a similar distribution of values for this parameter. As far as the baseline values are concerned, the nuclear power lifecycle has the highest EGR, but as mentioned in Section 3.1.5.6, this changes if the "opportunity cost" convention is applied.

GHG emissions (gCO_{2eq} /kWh)	High	Low	**Baseline**	Range
Offshore Wind Farm LC	21.85	9.37	**13.11**	12.47
Onshore Wind Farm LC	14.25	6.11	**8.55**	8.14
Nuclear Powerplant LC	10.24	5.74	**7.61**	4.50

Table 7.18 Summary of results for the normalised GHG emissions of the energy supply systems

The range of results for the normalised GHG emissions, show a more concise picture, with less variation between the baseline assumptions and the parametric variations. As can be seen from the table above, the nuclear power fuel cycle results vary only by 4.5 gCO_{2eq} /kWh, while the lifecycle also has the lowest emissions. The onshore wind farm then follows and finally the offshore wind farm performs the worst. Figure 7.16 represents more illustratively the ranges of the different systems and how they overlap.

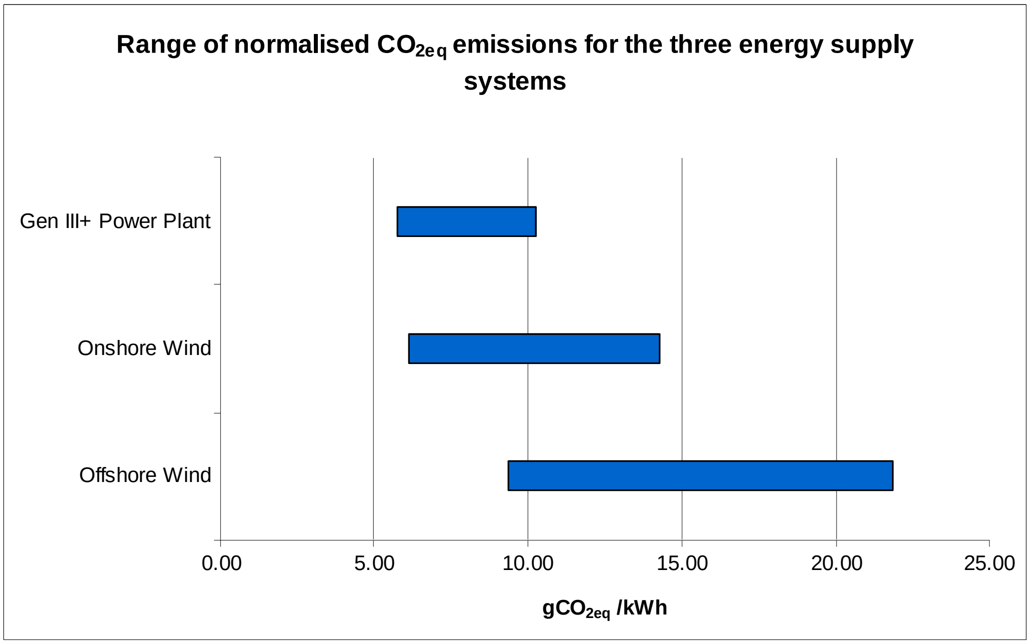

Figure 7.16 Range of GHG emissions from all three energy supply systems

Finally, the summary of the EPP shows that nuclear power has the largest variation of values as well as the longest payback period of the three energy supply systems. However, for the baseline case, all the technologies pay back with two and a half years.

Energy Payback Period EPP1	High	Low	**Baseline**	Range
Offshore Wind Farm LC	1.95	1.18	**1.54**	0.77
Onshore Wind Farm LC	1.17	0.84	**0.95**	0.33
Nuclear Powerplant LC	13.30	1.46	**2.01**	11.84

Table 7.19 Summary of results for the energy payback periods of the energy supply systems

7.5 Net-Energy Density

The concept of Net-Energy Density was fully outlined in the chapter on the methodology, so only a brief outline of the theory is given here. The Net-Energy Density ratio can be defined as the ratio of an energy supply system's net energy divided by total land consumption required to create and sustain the fuel chain. In broad terms, it is an indication of the amount of useful energy produced per unit of land area occupied.

The results for the Net-Energy Density of each energy supply systems are presented in Table 7.20. for two different units, and diagrammatically in Figure 7.17.

	Onshore wind LC	Offshore wind LC	Nuclear power LC
Net-Energy Density (km^2/TWh)	83.6	4.5	1.3
Net-Energy Density (GWh/km^2)	12.0	223.3	761.6

Table 7.20 Net Energy Density for the three lifecycles

The results in the above table are given in two different units. The two units are effectively the inverse of each other and therefore merely represent different ways of showing the same results. From these results, it is clear that the nuclear power life cycle, has a significantly higher Net-Energy Density compared to the other two life cycles being considered. The value for nuclear is approximately 60 times higher than that of the onshore wind farm and almost 3 times that of the offshore wind farm. A comparison between the two wind farms, results in the conclusion that the offshore wind farm performs significantly better than its onshore counterpart. An important point to be made about land requirements, especially for onshore wind farms, is that the land between turbines can still be used for other uses i.e. agriculture and grazing. In other words, the only surface area fully used in a wind farm, is the area required by the wind turbine foundations, any substations and the access roads. It has been estimated that wind turbines actually use approximately only 1% of the total wind farm allocated surface area. The NREL in the U.S., stated that a wind turbine requires approximately 0.25 - 0.5 acres of land (1,015 - 2,025m^2) (Jacobson, High, & NREL 2008). Using this approach (i.e. using the land take only of the facilities), and taking the upper range of the values for the requirements (2,025m^2), it was possible to re-calculate the Net Energy Density of the onshore wind farm. Using a total land requirement of 0.291 km^2, the Net-Energy Density was then calculated to be approximately 87.9 GWh/km^2 (or 11.4 km^2/TWh). Comparing with the previous results, it can be seen that when the land requirements are taken as the land use of the actual facilities, the Net-Energy Density increases by a factor of seven. The results however, are still lower than those for offshore wind and nuclear power.

Figure 7.17 shows the relative rankings of the three energy supply systems based on the above fact that onshore wind farms actually only permanently sequester a fraction of the land designated for wind farm use. For the graph the units of GWh_e /km^2 have been chosen as they were deemed more intuitive since they represent the amount of energy extracted for each unit of land area.

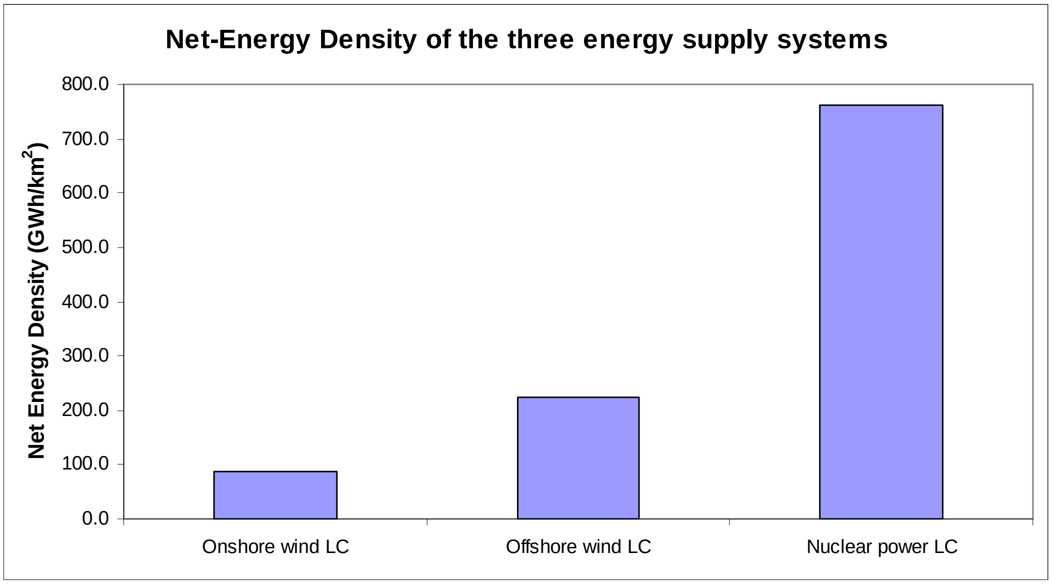

Figure 7.17 Net Energy Density (GWh/km2) for onshore, offshore wind and nuclear

Below, in Table 7.21, a summary of results from other relevant reports can be seen. These reports have already been highlighted in Chapter 2, in the Literature Review. From a comparison of the estimates with those of other publications, it can be seen that there is a high level of correlation between those and the current work.

Energy System	**L. Gagnon et al. (Gagnon, Belanger, & Uchiyama 2002)**	**EWG (Energy Working Group 2000)**	**Friedrich (Friedrich & Marheineke 1994)**	**Van de Vate (Van De Vate 1996b)**	**Lackner/ Sachs (Evans, Strezov, & Evans)**	**This work**
	(km^2/TWh)	**(km^2/TWh)**	**(km^2/TWh)**	**(km^2/TWh)**	**(km^2/TWh)**	**(km^2/TWh)**
Coal	4	3.63	1.68 - 22.16	-	-	-
Natural Gas	-	0.09	-	-	-	-
Nuclear	0.5	0.48	2.024	-	-	**1.3**
Wind	72	2.33 – 116.66	11.9 - 73.3	1	-	**4.5 (11.4[1]) /83.6**
PV	45	13.50 – 27.00	0 - 47.2	7.4	28-64	-
Biomass	533 – 2,200	1,320 – 2,200	-	-	-	-

1.Based on the fact that onshore wind turbines do not take up all the land assigned to the wind farm

Table 7.21 Summary of results for Net Energy Density from other studies

These results are a clear indication that if land use were to be become the deciding factor in the adoption of energy supply systems, then onshore wind would provide the least efficient option.

7.6 Water usage, material requirements and resource depletion

As part of the assessment of sustainability of the three energy systems under consideration in this work, an appraisal of certain other metrics was deemed beneficial. These additional metrics were defined based on outstanding issues affecting one or another (or all) of the energy supply systems under consideration. The specific background and definition of each metric have already been outlined in the Literature Review and the Methodology chapters. Each of the following sections outlines the results for the given metric, as well as giving a basic overview of the meaning of the results.

7.6.1 Water usage

The quantity of water used by energy supply systems is a metric that is often overlooked in their evaluation. However, as a result of the effects of Climate Change, water is likely to become a highly valued commodity in the future, so its utilisation and management could become crucial issues.

The water usage estimated in this project represents quantities of water used over the whole lifecycle for all three energy supply systems. The exact definition of the accounting methodology used has been described in Section 3.5.6, so it will suffice to say that the unit of measurement was defined as *m^3 of water permanently sequestered in the lifecycle / kWh of electricity delivered to end use*.

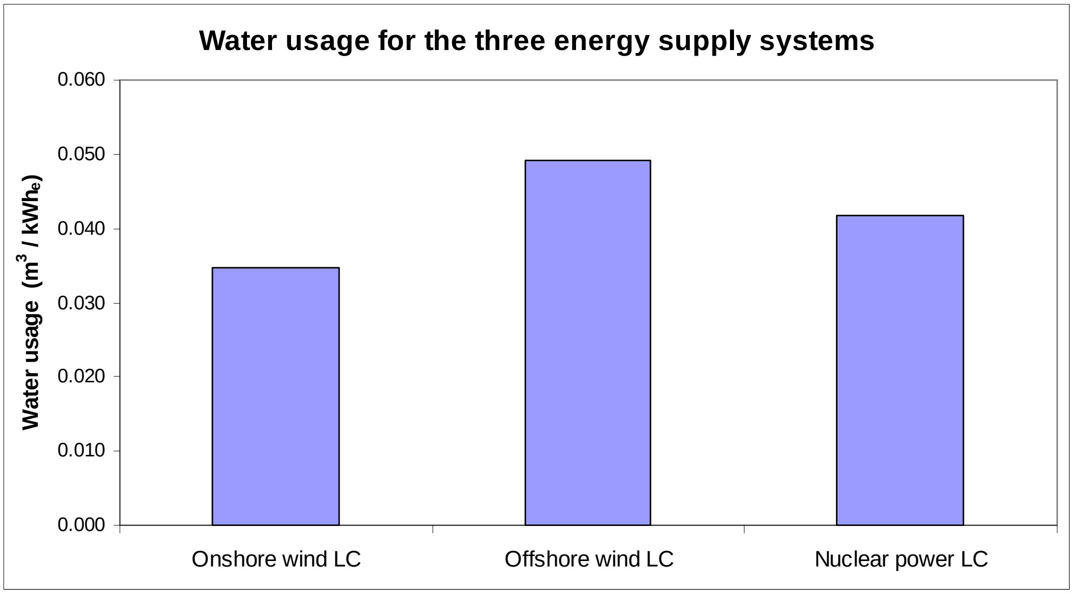

Figure 7.18 Water usage for the three lifecycles

Figure 7.18. above clearly demonstrates that the offshore wind power lifecycle has a higher level of water usage per kWh of electricity that it generates. This result is surprising as the wind farm does not use directly any water during its operation, in contrast to the nuclear fuel cycle which is, in effect, a conventional steam cycle. The nuclear fuel cycle also uses water extensively in the processing of ore to generate nuclear fuel. An inspection of the total amount of water used by each energy supply

system reveals that nuclear power does indeed utilise more water (1.88×10^{10} m^3) during its lifecycle, with offshore wind power in second place (3.21×10^9 m^3) and onshore wind in the last position (6.65×10^8 m^3). However, when these results are normalised by the electrical outputs of the stations, then the significantly higher output of nuclear power serves to counteract the large total quantities of water used. This has as a result the low permanent water sequestration values shown in the previous figure.

A detailed examination of the offshore wind farm lifecycle shows that the vast majority of the water usage can be attributed to the construction of the wind farm (Figure 7.19).

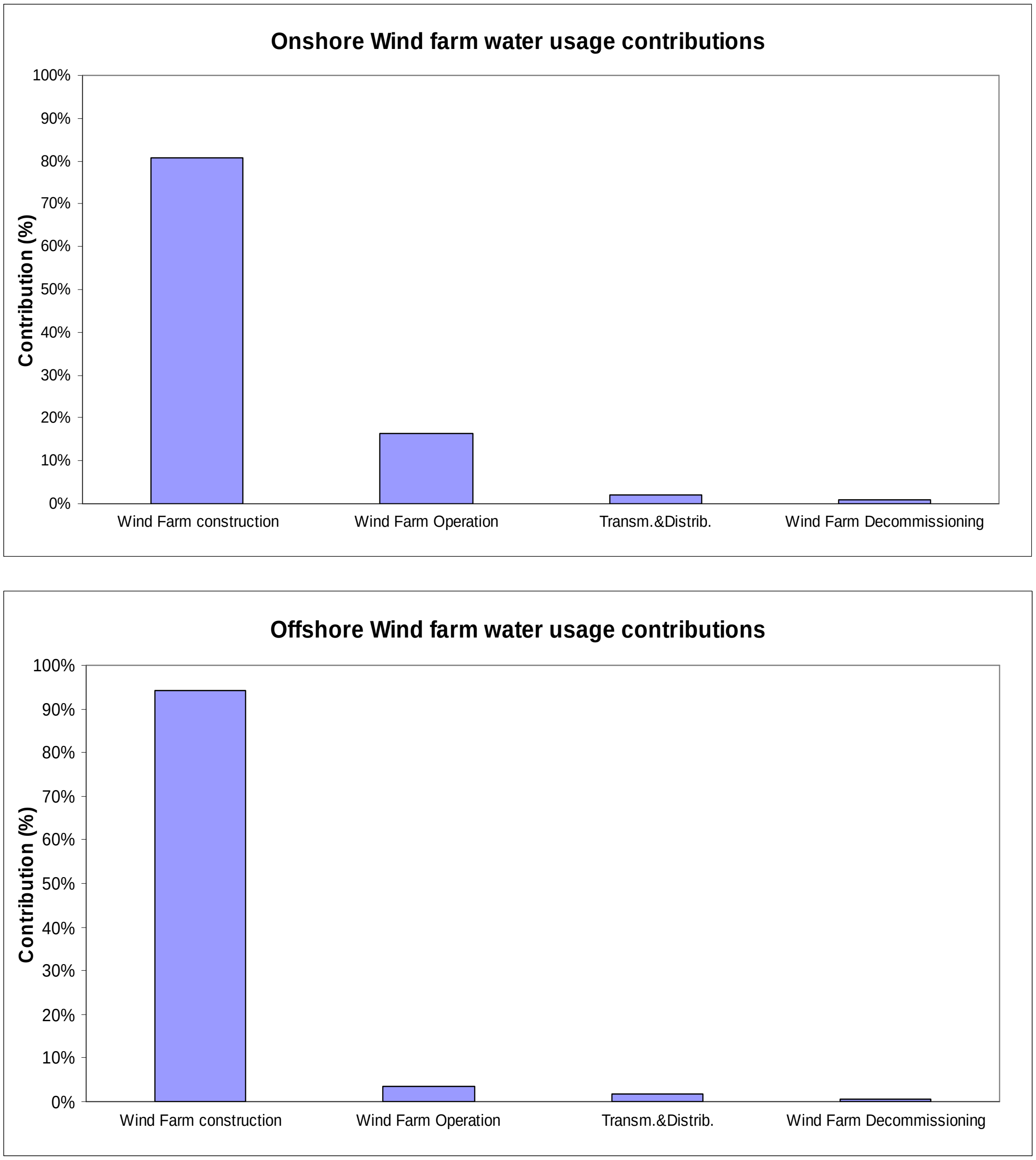

Figure 7.19 Water use per stage for the onshore and offshore wind farm

As can be seen from previous results, this lifecycle stage is mainly influenced by the manufacture of the wind turbines themselves (rather than other stages in the lifecycle e.g. the erection of the wind farm). This leads to the conclusion that the large number of wind turbines used are the reason for the high water usage rates. This is certainly related to the use of steel, which according to the results of the Ecoinvent database, uses 8.01 m^3 /kg compared to 0.221 m^3 /kg for concrete which is the other major construction material used in all three technologies. This then also explains why the onshore wind farm has lower values as the size of the wind turbines, and mainly the number of turbines, are much lower.

7.6.2 Material requirements

A metric occasionally quoted in literature is that of the material requirements different energy supply systems would have, if adopted. The purpose of this metric is to highlight the effect different construction requirements could have on various building materials, in the event that these were in scarce supply. It also serves as an indication of the likely cost implications for the different technologies, as a high demand for certain materials, which are high priced commodities, will have a knock-on effect on financial viability of the project. An indication of this could be seen in the commodities market in 2007, with the high prices of steel causing problems in the supply chain of wind turbines (Aubrey 2007).

As such, each of the three energy supply systems under consideration was analysed to establish the quantities of material required to construct the power plants. As highlighted in the methodology chapter, these quantities represent the direct material requirements for the construction of each power plant, rather than the whole lifecycle requirements. Although this is a departure from the boundary conditions defined in the methodology, as was stated there, it is required as the definition of this metric for the whole life cycle would be nearly impossible due to allocation issues. In order for this comparison of requirements to be meaningful it was necessary to normalise the quantities, as was done with other metrics, to provide a common basis. In this case the unit of normalisation was again taken to be a unit of energy produced by the power plants (kWh_e). The choice of materials chosen for the comparison is based on the most common construction materials used in energy supply systems and in large construction projects. Specifically, the options were based on the materials that were common to all three systems and/or were the largest contributors to the total mass of materials for each technology. As a result, certain materials listed in the bill of materials provided in the Appendices are not compared here. A summary of the results can be seen below in Table 7.22:

	Onshore wind farm	**Offshore Wind Farm**	**Nuclear Power Station**	
			Baseline	**1971 data (ORNL, Resources for the Future, & DoE 1995)**
Material	***Unit: kg/ kWh$_e$***			
Steel	1.55E-03	3.84E-03	5.16E-05	7.17E-05
Iron	1.52E-04	2.22E-04	n/a	2.59E-06
Concrete	5.69E-03	4.51E-04	1.74E-03	3.71E-04
Copper	1.04E-04	1.18E-04	n/a	1.43E-06
Aluminium	1.08E-06	1.55E-06	n/a	3.71E-08
Fibre glass	2.11E-05	3.09E-05	n/a	n/a
PVC	8.96E-06	1.12E-05	n/a	n/a
PE	1.54E-06	2.30E-06	n/a	n/a
PA	5.15E-07	7.67E-07	n/a	n/a

Table 7.22 Direct construction material requirements for all three technologies

For the nuclear power station, the results for two different data sets are presented, one using the Baseline Scenario, with data from (DoE 2005) and the other based on the 1971 design as given in (Bryan & Dudley 1974). From these results it can be seen that despite the fact that the nuclear power stations require significantly larger quantities of materials than either of the wind farms, once normalised by the electricity generation, the material requirements are roughly of the same order of magnitude. Figure 7.20 shows the normalised requirements for steel and concrete, the two main construction materials:

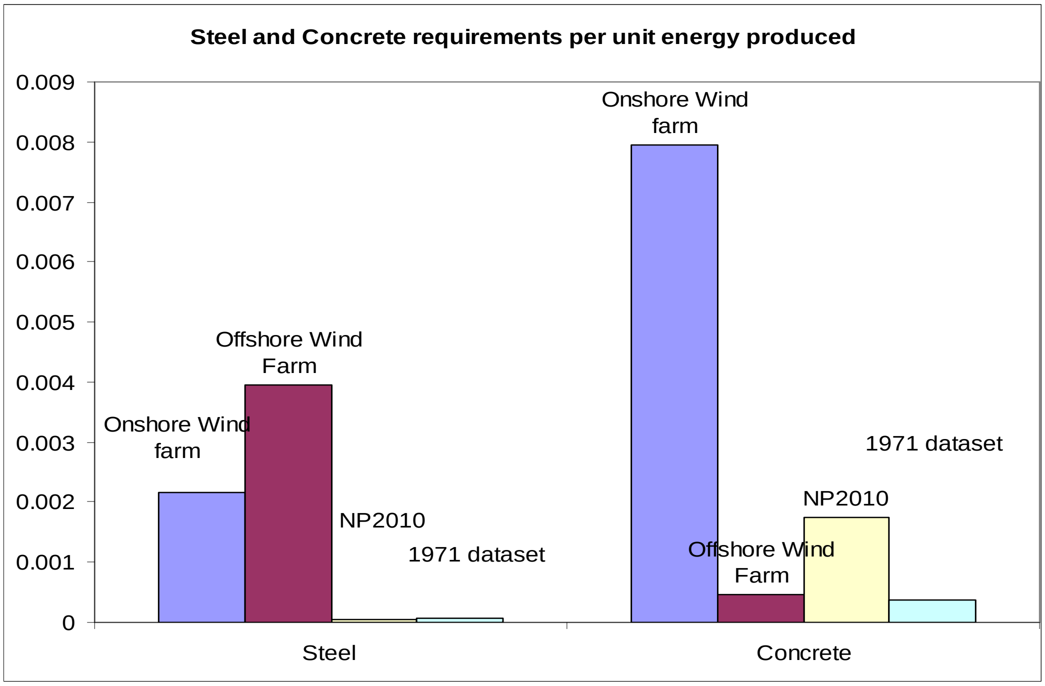

Figure 7.20 Normalised steel and concrete requirements for all technologies

The results are similar to those quoted in previous studies, such as that of Inhaber (2004), where to the conclusion reached was that nuclear and wind power have similar material requirements.

7.6.3 Resource Depletion

The three energy supply systems were also analysed to see their impact on resources, as defined in the Methodology Chapter. Once again they have been normalised by the electrical output of the power stations. The results are split up over 4 figures, as the different orders of magnitude of the values for each material did not allow a combined graph.

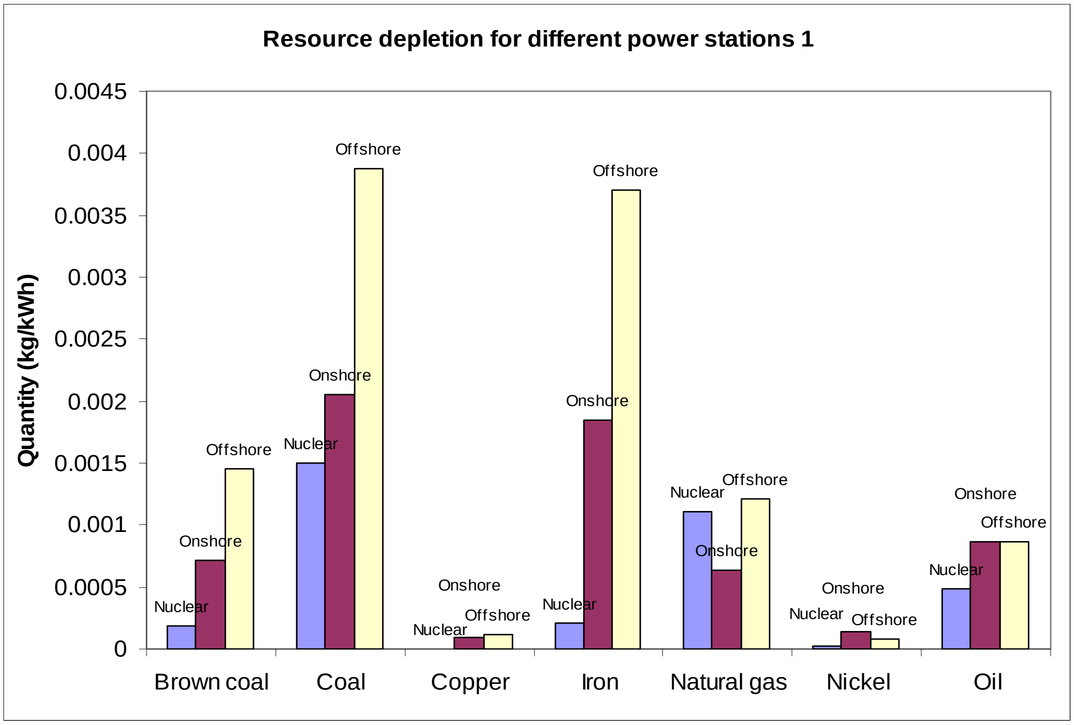

Figure 7.21 Resource depletion results (first group of results)

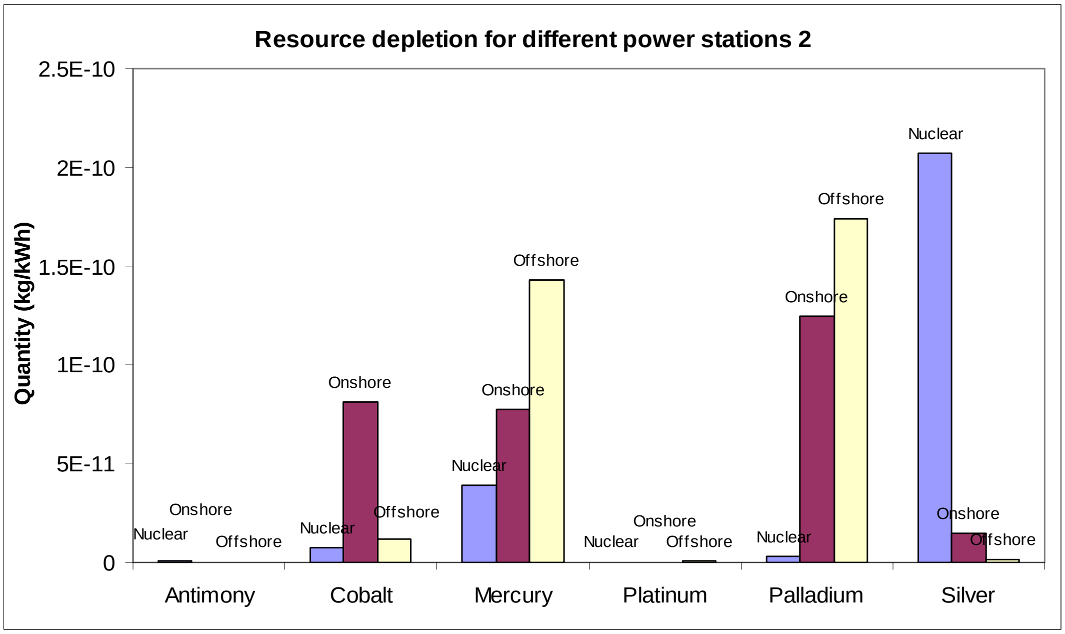

Figure 7.22 Resource depletion results (second group of results)

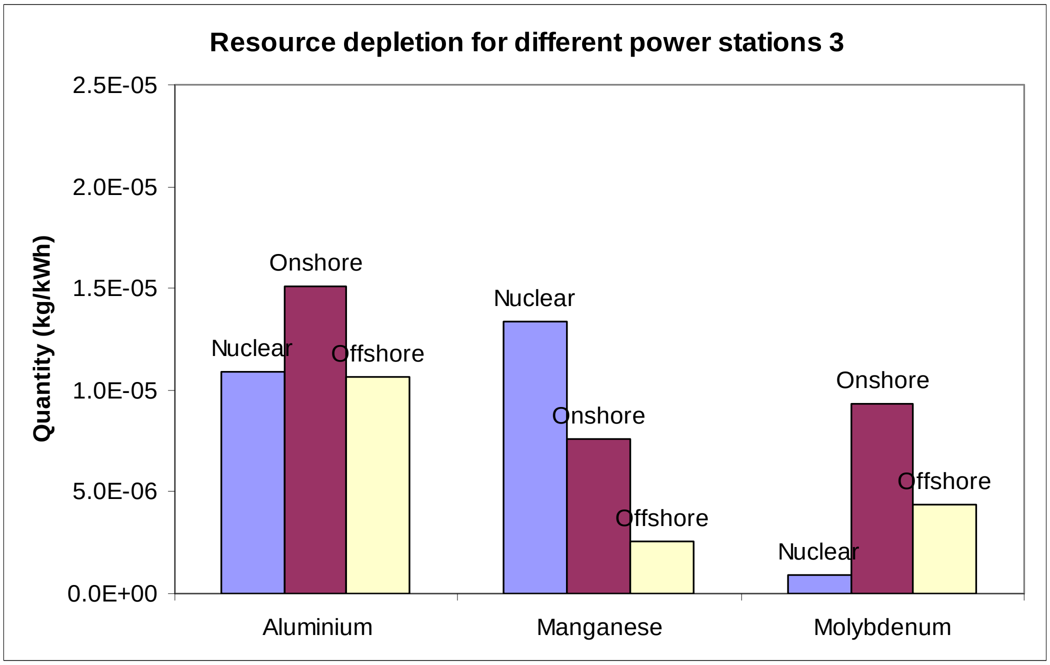

Figure 7.23 Resource depletion results (third group of results)

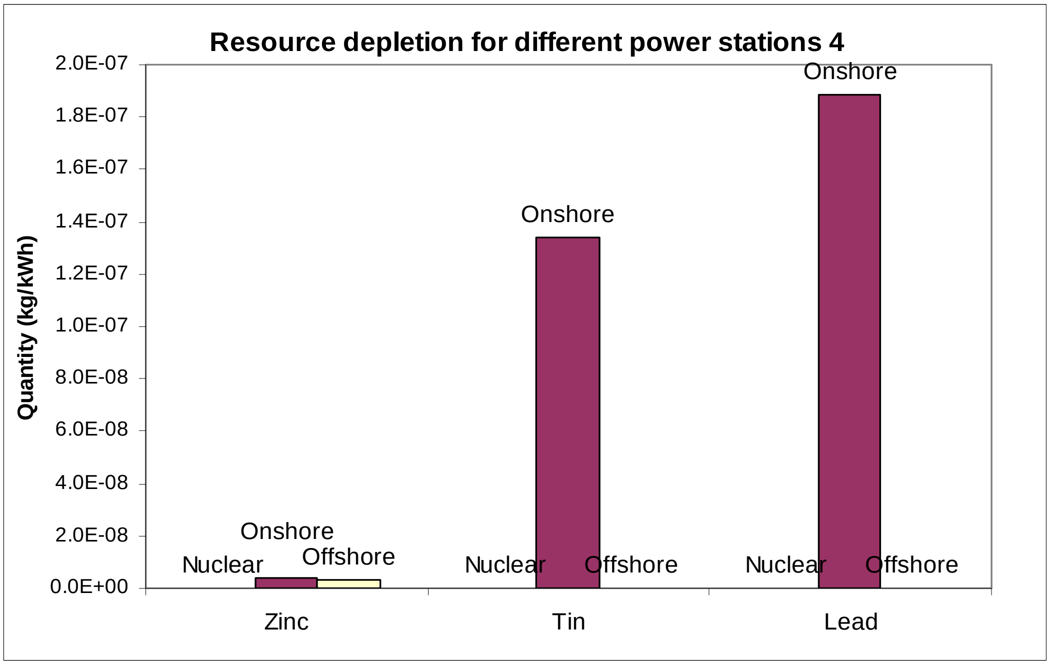

Figure 7.24 Resource depletion results (fourth group of results)

From the above figures it can be observed that nuclear power has lower requirements in almost all categories than the two wind farm technologies. With respect to wind power, there is an almost even split in the number of categories they dominate for onshore and offshore wind.

7.7 Avoided Carbon Dioxide Emissions

As a completely different dataset was required for this assessment, it was felt that the results would be most clearly represented and displayed if the whole calculation process was exhibited separately from the other parameters.

The calculation of the avoided emissions was based on the guidelines set out in (World Resources Institute & Broekhoff 2007), which provides an analytical framework with which to define the different parameters that influence this indicator. The following sections detail the procedures followed as well as any assumptions that were required in order to create an "avoided emissions" factor for the 3 technologies being investigated, under current U.K. conditions. It is important to note that this section deals strictly with avoided *carbon dioxide* emissions (mass units of CO_2), in contrast to earlier sections where *greenhouse gas emissions* have been described (which have been measured in mass units of CO_2 *equivalent*). This has been brought about by the fact that the available information on power plant emissions is provided in that unit of measurement and not in the more generic carbon dioxide equivalent emissions.

7.7.1 The relative contributions of the Built and Operating Margins

As stated in the methodology section, one of the first tasks in the process of estimating the quantity of avoided carbon dioxide emissions from the implementation of a near-zero carbon technology, is to determine to what extent the technology affects the Built and Operating Margins. As Equation 3.10 demonstrates (Chapter 3), this effect is incorporated into the calculations based on the weighting factor *w*, which can take a value between 0 and 1. The main determinant of this weighting is related to the technology's ability to meet demand for new capacity, therefore displacing other capacity at the BM. If the Grid into which the technology is being incorporated has enough capacity to meet current and future demand, then the weighting will have a value closer or equal to zero. Thus the operation of the energy supply system will only affect the operation of current capacity by limiting the need for them to operate (therefore affecting the OM). If, on the other hand, there is chronic under-capacity in the grid in question, then the weighting factor *w* will be closer to 1, representing the fact that the effect of the technology will be felt at the BM.

As discussed in Chapter 2, repeated warnings that the U.K. could be facing blackouts because of a shortfall of generation capacity in the coming decades were expressed by various commentators. Thus, it was felt that the implementation of nuclear and wind power projects would definitely be required to meet capacity and therefore would have an effect on the BM (i.e. *w* would not be zero). Since the projects being considered would be meeting demand for new capacity, its relative effect on the BM (or more specifically the value of *w*) would be defined in proportion to its capacity value, as was stated in (World Resources Institute & Broekhoff 2007). The appropriate value for *w*, will either be 1 or the ratio of the project's capacity value (or capacity credit) to its average utilisation in megawatts (i.e. its installed capacity multiplied by its load factor), whichever is lowest:

$$w = \min\left(1, \frac{CAP_{value}}{CAP_{rated} \times CF}\right) \qquad (7.1)$$

where

- CAP_{value} is the project activity's capacity value in megawatts
- CAP_{rated} is the rated capacity for the project activity –
  i.e. the power it is physically capable of delivering, also
  called the "nameplate" capacity
- CF is the expected capacity factor (i.e., percentage
  average utilization) for the project activity.

The capacity value is determined by the extent to which the energy supply system can deliver firm power as well as the timing of the delivered power with respect to the times of peak demand on the grid. For the purposes of this analysis, a firm power plant is considered a power plant that can be *consistently relied upon* to supply power to the grid, when this is required. It should be noted that no power plant can be considered completely firm, i.e. completely reliable without any outages or down-times. As such, a "firm" power plant here is used in the sense of "available and dispatchable" a very high percentage of the time that it is called upon to do so. A technology that can supply firm (i.e. non intermittent) power at all times will be assigned a value of *w* = 1. On the other hand, even if the source is intermittent, if it provides firm power specifically at periods of high demand then it is possible to have a capacity value larger than its level of continuously reliable generation, and hence by the previous definition, a value for *w*=1. Technologies with *w* values less than 1 will, by definition, affect both the OM and the BM. As can be seen, the estimation of the weighting factor *w* is a complicated issue, and as such, (World Resources Institute & Broekhoff 2007) provides the following guidelines shown in Table 7.23., where the exact definition of *w* is impractical:

PROJECT ACTIVITY	FIRM POWER	NON FIRM POWER
On-peak, baseload, or intermittent generation	Capacity Value: High **100% BM** ***w* = 1**	Capacity Value: Low **50% BM + 50% OM** ***w* = 0.5**
Exclusively off-peak generation	Capacity Value: Low **50% BM + 50% OM** ***w* = 0.5**	Capacity Value: Zero **100% OM** ***w* = 0**

Table 7.23 Default weighting values based on technology capacity value

The first step to implementing the above methodology then, is the definition of capacity value of the three energy supply systems under consideration.

Nuclear Power

Based on the role of nuclear power stations in the Grid as baseload operators (i.e. very high capacity value) and their ability to provide firm power, using the definitions given in Table 7.23 above, it can be seen that the most appropriate factor for the weighting figure would be 1.

Wind Power

For the calculation of the weighting for the two wind farms, it was necessary to calculate their capacity value. The capacity value can be generally defined as the quantity of conventional generation that could be displaced by renewable production, without making the system less reliable (Pudaruth & Li 2008). Thus, the capacity credit of renewables is the faction of their rated power that can be considered ‘equally reliable’ as its conventional alternative (Voorspools & D'haeseleer 2006). The definition of the capacity value of wind has been a subject of intense research, as it is of fundamental importance to grid operators and planners. Many studies have been conducted on this subject, as can be seen in reviews provided by (Pudaruth & Li 2008) and (Giebel 2005). Most methods of evaluation are based on statistical methods and use concepts such as the Loss of Load Probability (LOLP) or Effective Load Carrying Capability (ELCC). These methods tend to be data intensive and require detailed computer models to be built, that implicitly model the whole grid and the interactions of the different generators. However, other methods based on more heuristic approaches are also used, particularly by electricity utilities and grid operators in the U.S., as can be seen in the report by (Milligan & Parsons 1997) and (Milligan & Porter 2005). This approach was also used in the current work, as it was felt that it would provide a first estimate of the wind farms capacity value, without resulting in an excessive amount of workload.

The method is based on the evaluation of the capacity factor for the wind farm under investigation, during the times of the grid’s peak load. Specifically, it involves defining the capacity factor at the top 30% hours of peak demand and then using the average as the capacity credit of the wind farm. A similar approach is utilised by several grid operators in the U.S., as described in (Milligan & Parsons 1997), and has been adapted to the needs of this study. The definition of the U.K.’s period of peak loading was estimated from the data provided in the National Grid's (U.K. electricity and gas network operator) Seven Year Statement. As can be seen from Figure 7.25 (taken from (National Grid plc. 2007)), taken from that Statement, the period of peak demand for the U.K. grid is between Weeks 31 through to 47, which corresponds roughly to the months of November through to January, inclusive.

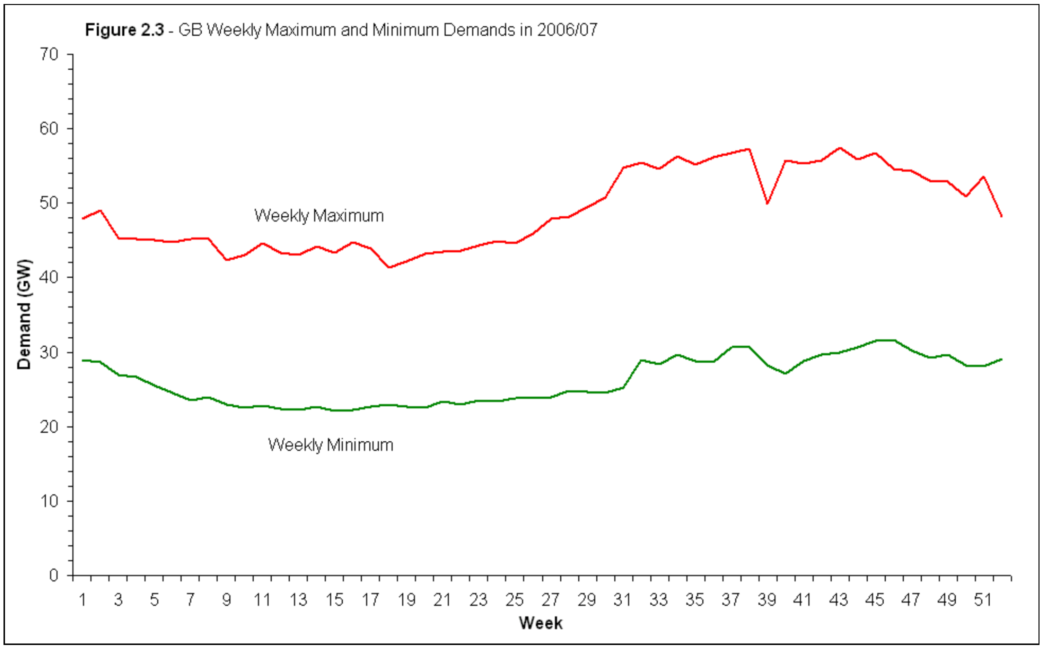

Figure 7.25 Weekly demand for 2006/2007

A closer look at the hourly demand profiles, shown in Figure 7.26 below (taken from (National Grid plc. 2007)), shows that the top 30% of hours of peak loading, during hours of peak demand (i.e. the demand between November and January), are approximately 7 hours between 15:00 – 22:00 daily.

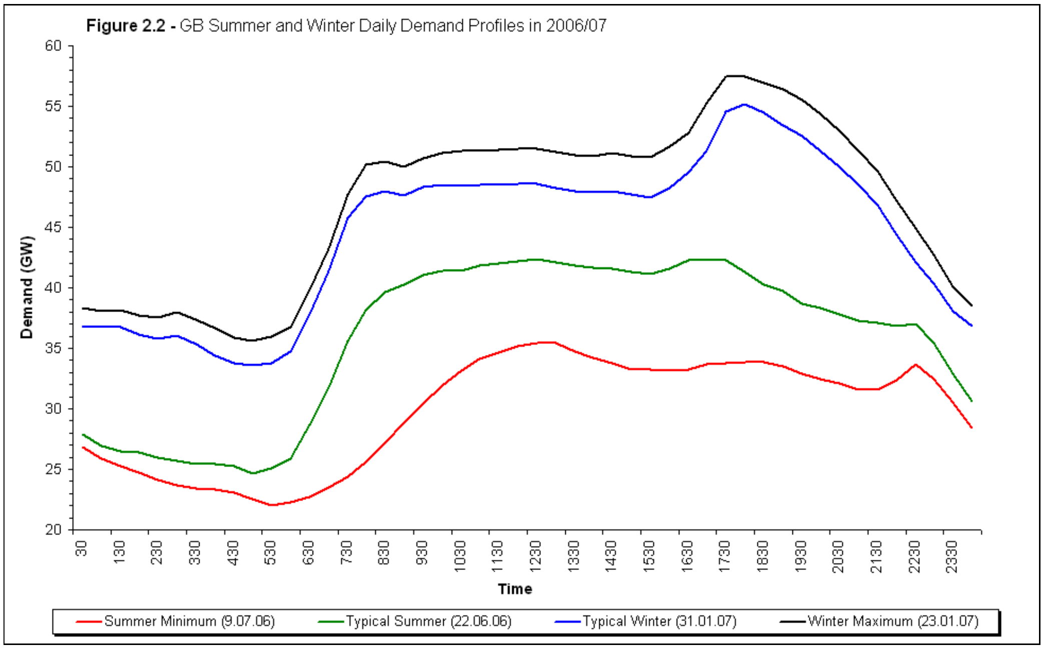

Figure 7.26 Daily demand profiles for 2006/7

Using this information and the hourly wind speeds for the onshore wind farm, it was then feasible to estimate the capacity factor for the wind farm, during these hours of peak demand. As this method was primarily used, as a first instance, to provide an indication of the feasibility of the method, the investigation using the above constraints (i.e. time and date of peak demand), was applied to the windspeed dataset only at 5-year intervals (i.e. years 1990, 1995, 2000 and 2005). The results from the analysis indicated that the average capacity factor for this period (42.6% once array losses were included) was actually very marginally higher than the long term average for the lifetime for the wind farm (42.5%). This would indicate then that the capacity value of the wind farm (42.6% x 210MW = 89.5MW) was actually almost identical to its average utilisation in megawatts, as detailed in equation 7.1, in Section 7.1.1.

Returning to the methodology for calculating avoided emissions, the above result would give a weighting value in excess of 1. However, as stated before, the method only provided a “rule of thumb” estimate, and only applicable to the onshore wind farm for which analytical wind speed data existed, so it was decided to investigate the capacity value of wind power using other methods.

A further estimation of capacity value was calculated using the analytical formulas presented in (Voorspools & D'haeseleer 2006). The methodology for this formula was formed using published values and is based on the penetration level of the wind power in the power system, the overall capacity factor of the wind turbines under investigation, the reliability of the conventional generation of the power system and the spread of the wind turbines. The main advantage of this method was that it provided a quick estimate of the capacity credit, without requiring the calculation-intensive approach of stochastic methods. The equation, as formulated in (Voorspools & D'haeseleer 2006), is as follows:

$$CC = \frac{U}{V + d}\frac{CFwind}{Rsystem}\left(1 + W\delta e^{-Y(V+\delta)(x-1)}\right)\ for\ x > 1\% \quad (7.2)$$

$$CC = \frac{U}{V + d}\frac{CFwind}{Rsystem}\left(1 + W\right)\ for\ x < 1\% \quad (7.3)$$

where *CC*: capacity credit in % of installed rated wind power
x: penetration level of wind in % of peak load
CFwind: capacity factor of wind project in %
Rsystem: reliability of conventional plants in %
U: 32.8
V: 0.306
W: 3.26
Y: 0.1077
δ: dispersion coefficient
δ=0: perfect spread
δ=1: no spread

In order to apply the formula, it was first necessary to establish the penetration level of wind in peak load. From the Seven Year Statement (National Grid plc. 2007), it was found that the peak load for 2006/2007 was estimated to be 58,400MW, which meant that the onshore wind farm's penetration represented approximately 0.4% of the peak load (necessitating the use of equation 2), while for the offshore wind farm, this figure was 1.7% (represented by equation 1). Using a case study cited in (Voorspools & D'haeseleer 2006), the dispersion coefficient for both wind farms was set at 0.96. This was deemed accurate, since the above equations were formulated from the study of wind farms dispersed over the country of the Netherlands, so the dispersion of a single wind farm could be assumed insignificant by comparison. Finally, the value for the reliability of the U.K. Grid, was based on the estimate used by the now defunct U.K.'s Central Electricity Generating Board, which was responsible for the National Grid, prior to privatisation. It was estimated that the grid then operated with a LOLP of 9% (i.e. reliability of 91%) (Strbac et al. 2007).

Using the above equations and the values for the parameters as outline above, the capacity credit of the onshore wind farm was estimated to be in the region of 39%, while that of the offshore wind farm was calculated to be approximately 34.1%. In this method as well, the capacity credit for both wind farms exceeds their normal average capacity factor, thereby giving weighting factors for *w*, above the range (0< *w* <1). After further consultation with the guidelines for calculating the avoided emissions (World Resources Institute & Broekhoff 2007), it was revealed that, in cases where the project's "reliable output is higher (or lower) during times of peak demand than at other times, its designated capacity value may be too high (or too low) for the purpose of determining displaced BM capacity". Given this conclusion, the decision was taken to utilise a conservative estimate, based on the guidelines in Table 7.23, and adjust to equal weighting to both the Built and Operating margins (*w* equals 0.5 for BM and 0.5 for OM). This weighting was then used throughout the study of avoided emissions.

It should be noted that in reality these approaches of calculating the capacity value of wind power would have to be undertaken for all wind power derived electricity generation and not just for specific wind farms. However, as the purpose of the exercise is to calculate a weighting factor for the specific wind farms under consideration, this truncation was necessary.

7.7.2 Estimating the Built Margin (BM) emissions factor

The guidelines specify three methods for defining the BM emissions factor, which vary with different parameters such as relevance, transparency, accuracy and so on. A description of each has already been provided in the methodology section, so here only a brief explanation of the chosen method for this work will be given.

For the purposes of this research, the *performance standard* procedure was chosen to estimate the Built Margin's emissions. The procedure is based on the calculation of an emissions factor that represents the blended emission rate of the identified baseline candidates. The baseline candidates represent the alternative technologies that could be used to provide the same product (i.e. grid-connected electricity generation) as the power plant in question. For these technologies to be considered baseline candidates, they must be found within the same geographical area, which for this study is the U.K., and must have commenced generation within a certain time frame. In effect, they represent what could have been built instead of the power plant in question to provide the same generation. The baseline candidates are usually taken to be recent capacity additions to the grid as well as under-construction and planned capacity (World Resources Institute & Broekhoff 2007).

7.7.2.1 Identifying the Baseline candidates

As stated in the above section, the baseline candidates have to provide the same service/product as the power plant under investigation. Whereas it is obvious that all alternatives must produce electricity to be considered, an important factor that also influences the definition of product is that of the timing of generation. This is important because not all power plants can provide the same service to the grid. Certain power plants are best at, or can only provide baseload generation, while others such as renewables provide intermittent generation. Others still can provide dispatchable power, such as hydro and CCGT power plants, and are termed load-following. According to the guidelines, baseload generators are assumed to be able to replace all other forms of generation (by increasing their production they can displace other baseload or even minimising the use of load-following), while load-following power plants are assumed to dispatch only similar plants (as they would not be used to displace baseload, due to operational but mainly financial reasons; baseload is cheaper to run). A further distinction must be made between so called “must-run” and “intermittent” power plants. The former encompass those plants whose operation is required to ensure the reliable transmission and delivery of grid electricity, while the latter category covers power plants who operate variably as a result of the availability of their primary fuel (i.e. renewables) (World Resources Institute & Broekhoff 2007). For the purposes of this analysis, “must-run” and “intermittent” power plants are treated as functionally equivalent to “baseload” power plants, since they do not respond to changes in load.As a result, it is important for the definition of the baseline candidates to establish what form of generation the power plants in question fall under.

Using the rules outlined above, nuclear power was deemed to fall under the category of baseload, as it fulfilled the criteria of having a high-capacity factor and being operated under a “must-run” regime. The onshore and offshore wind farms were also designated as “baseload” for the purposes of this analysis, since under the rules set out in the guidelines, intermittent and “non-firm” capacity generators also belong to this category. As a result of this classification, the baseline candidates for both nuclear and wind power plants should include all baseload and load-following power plants recently added to the grid.

7.7.2.2 Defining the Geographical Boundary and Temporal Range

As the three power plants are assumed to be connected to the U.K. grid, the geographical boundary included all power plants connected to the National Grid and under its control (common TSO). The guidelines suggest that the baseline candidates should be restricted to recently built, planned or under construction, providing the same type of power as the project activity. To ensure a representative sample, it was stated that this should include the most recent 20% of capacity additions (as measured against total grid capacity). The guideline then go on to state that the temporal range should not extend beyond the most recent 5-7 years. However if the requirement of 20% of installed capacity is not available in this time period, then the temporal boundaries can be expanded to include “planned” and “under construction” capacity.

The U.K.'s National Grid has a total installed capacity of 77,376 MW, based on the information provided in Table 5.11 in (DTI 2007a), meaning that 20% of the Grid installed capacity is 15,475 MW. Using the data in the aforementioned table in the previously mentioned source, in the period 2000-2007, there has been an increase of capacity totaling 9160 MW. A summary of the types of power plants commencing operation in the period of 2000-2006 can be seen in the Table 7.24 below, while an analytical representation can be seen in Appendix D:

Type of power Plant	Number of plants	Rated capacity (MW)
CCGT	10	5958
Wind	43	1129
CHP	2	921
Coal	1	393
Other[1]	4	638
Diesel	1	3
Hydro	10	69
Gas	5	50
TOTAL	**76**	**9160.9**

1 includes unconventional power stations (i.e. biomass, mine gas) as well as stations that generate specifically for industry use (i.e Baglan Bay which generates electricity for the local business park as well as generating for the National Grid)

Table 7.24 Summary of power plants that commenced operation in the period 2000-2007

In order to fulfill the quota of capacity (15,475 MW), it was then necessary to consider future additions to the Grid. This was attempted by consulting the power plant applications that had recently been approved for construction by the U.K. Government. These were listed in (BERR 2008a). Using this source, Table 7.25 provides a summary of recently approved power plant additions to the Grid.

Type of power plant	Number of approved applications	Rated Capacity MW
Wind	11	3024
Wave	2	20
CCGT	6	5140
Biomass	1	350
Others[1]	6	1270
Waste	1	70

1 includes increases to capacity to currently operating power plants through upgrades. As these were not considered "new" power plants but just upgrades to current ones, they were not included in this assessment.

Table .7.25 Recently approved power plant additions (2009)

The total added capacity as a result of these additions was then calculated to be a further 8600MW. When combined with the capacities of the recently added power plants during the period 2000-2007, the total capacity equaled 17,765MW which was within the 20% range required by the guidelines.

7.7.2.3 Final List of Baseline candidates

Using the above conditions, an extensive list of candidates was compiled, as can be seen from the tables in Appendix D. A summary table is provided below which details the type of power plant being added, and is ordered by rated capacity. From this table, it can clearly be seen that recent and projected grid capacity increases are dominated mainly by wind power and CCGT plants. This can also be seen when the plant additions are ordered chronologically, since the recent consented additions are all either wind or CCGT projects. However, in order to fulfill the 20% criteria guideline, Combined Heat and Power (CHP) were also included in the final list of baseline candidates (totaling 16,172MW). This particular type of power plant was chosen since it was also a common choice of power plant chronologically as well as by rated capacity.

Type of power plant	***Projects***	***Rated Capacity (MW)***
CCGT	16	11098
Wind	54	4153
CHP	2	921
Other	4	638
Coal	1	393
Biomass	1	350
Hydro/wave	12	89
Waste	1	70
Gas	5	50
Diesel	1	3
	Total	**17765**

Table.7.26 Summary of powerplants considered for baseline candidates

7.7.2.4 Justifying the baseline scenario and characterising the BM

The next step in the definition of the baseline candidates is the justification stage. In this stage a comparative assessment of the barriers facing the baseline candidates as well as the proposed technologies is investigated. The purpose of the comparative assessment of barriers is to demonstrate that the technologies being proposed face more significant barriers than the baseline candidates and therefore cannot be considered themselves as part of the baseline scenario. As such, the purpose is to establish the technologies' *additionality*. Specifically this can be done by showing that *at least one* of the baseline candidates faces significantly lower barriers than the technology being investigated (in the case of this work, onshore/offshore wind and nuclear power).

From the analysis of the top 20% of current and planned additions to the Grid over the last 7 years, it is clear that of the 15,475 MW required for the assessment, approximately 72% is from CCGT plants, wind power projects (offshore and onshore) represent almost 27% and the remainder is made up by the CHP plants. According to the guidelines, it is permissible to create "representative" power plants which have common characteristics, in the event that the number of candidates does not allow an individual listing. As a result, the baseline candidates have been grouped into 3 representative plants, and their barriers assessed against those of the three technologies being considered in this project.

	Capacity	Function	Financial and budgetary	Technology O&M	Infrastructure	Market Structure	Institutional/ Social/ Cultural/ Political	Total	**Rank**
Onshore Wind	210MW	Intermittent / Baseload	2	2	3	1	3	11	**3**
Offshore Wind	1000MW	Intermittent / Baseload	3	3	2	2	2	12	**2**
Nuclear Power	1117MW	Baseload	3	3	3	3	3	15	**1**
Average CCGT	660MW	Load Following	1	1	1	1	1	5	**4**
Average Wind r	27MW	Intermittent / Baseload	2	2	2	2	3	11	**3**
Average CHP	460MW	Load Following	2	3	1	2	1	9	**5**

Table 7.27 Assessment of barriers for baseline candidates and project activities

The 6 power plants were assessed according to the categories listed in the above table. A definition of each category is provided in the guidelines and a summary of what is assessed in each is given the table below, taken from (World Resources Institute & Broekhoff 2007):

Barrier Type	**Barrier Examples**
Financial and Budgetary	• Upfront capital costs
	• Cost of delivered electricity(e.g. levelized $/kWh)
	• Cost of fuel
	• Cost of materials (e.g. for construction or maintenance)
Technology Operation and Maintenance	• New or unproven technology • Technology with demanding technical or operational requirements
Infrastructure	• Physical siting requirements
	• Availability of fuel
	• Availability of materials
	• Availability of waste disposal infrastructure (e.e for nuclear)
	• Lack of manufacturing or delivery capacity for relevant technologies
Market Structure	• Lack of capacity demand (e.g. excess power capacity of a capacity overbuild)
	• regulatory conditions or market constraints that disfavour capital investments for a particular technology
	• Perception or informational market barriers (consumer failure to understand the benefits of energy savings)
Institutional/ Social/ Cultural/ Political	• Permitting and other regulatory requirements
	• Public perceptions and acceptance

Table 7.28 Explanation of categories for assessing barriers

Based on the above, a rating score of 1-3 (with 1 representing a low and 3 a high level of difficulty) was used to order the relative positions of each power plant. The scores in each category were then added to provide a final ranking score, with low number demonstrating the technology least affected by the barriers and a high score representing a project that faced significant barriers. From the assessment, it can be seen that both the wind farm and nuclear power plants face more significant barriers than CCGT plants and CHP projects, therefore justifying their non-inclusion as baseline candidates. Naturally, there is a certain degree of ambiguity and subjectivity to the assessment scores. However, it was felt that the final rankings represented fairly accurately the current level of acceptability for the various technologies.

7.7.2.5 Estimation of the BM emissions factor

With the above stages complete, the final step related to the Built Margin is the estimation of the BM emissions factor. As stated previously, the approach used in this research was based on the performance standard procedure. The requirements for this procedure include the total generation of each power plant in the baseline scenario over a year and the total carbon dioxide emissions over the same period. This information was then used to create a blended emissions rate, which was weighted by the relative contributions of each station.

Although the detailed information specified above was not available for the baseline scenario, certain assumptions were made. In order to calculate the total generation over the period of a year, the rated capacity of each power station was multiplied by the average load factor for the power plant type, as specified in Table 5.10 of the Digest of U.K energy statistics (DTI 2007a). The emissions from each power plant (for the currently operational CCGT and CHP facilities) were taken from their declarations to Phase II of the U.K. emission trading scheme (DEFRA 2007) and were therefore completely representative of the carbon dioxide emission emitted. It must be noted, that associated emissions with wind power at the point of electricity generation were taken to be 0. For the recently consented projects, there was of course no operational data so a similar approach was used to that previously described. The rated capacity of each power plant was multiplied by the load factor of the operating power plants, as it was assumed that due to the relatively young age of the power plants included in the baseline scenario (i.e. less than 8 years operation) their load factors would be representative. A similar approach was used with the emissions factor, where the factor for currently operating plants was attributed to future additions. In order to calculate the emission rate per type of power plant, the total attributed carbon dioxide emissions were divided by the total generation of the power plant type, therefore giving an average emissions factor per power plant category. This approach was chosen at this stage (instead of the “weighted mean” used later on), as it was not felt that the level of data used was accurate enough to justify more elaborate methods.

With the emission factors for each power plant type in the baseline scenario defined, the final step in the procedure was the calculation of the carbon dioxide emission rate for the Built Margin. The method chosen for the definition of this emission rate was based on the weighted mean fraction, as can be seen below:

$$Weighted\ mean\ emission\ factor = \frac{\sum_{i=1}^{n}(ER_i \times Q_i)}{\sum_{i=1}^{n}(Q_i)} \qquad (7.4)$$

Where:

- ER_i is the carbon dioxide emission rate of baseline candidate i.
- Q_i is the generation in kWh produced by baseline candidate i over a certain time period. The time period should be the same for all baseline candidates, and should coincide with the time period used to determine the emission rate, ER_i.
- n is the total number of baseline candidates.

The application of the above formula to the baseline candidates resulted in the calculation of the Built Margin emissions factor:

Built Margin emission factor	**495.2 gCO_2 / kWh**

7.7.3 Estimating the Operating Margin (OM) emissions factor

The emissions factor for the OM represents the emissions that would be saved by backing down other power plants on the grid, in response to the output of the project technology. Ideally, a detailed knowledge of exactly which type of plant was being withdrawn would allow for an accurate calculation of the emissions saved. However, this in practice is impossible, especially in privatised electricity markets such as the U.K.'s where the dispatching of various plants is based on a variety of non-transparent economic factors. Given these restrictions, several methods are proposed in (World Resources Institute & Broekhoff 2007) to provide as accurate an estimate as possible using the information generally available. These methods have been outlined in the Methodology Chapter (Chapter 3), so a description of only the two methods employed in this work are described in detail here: the "average load-following" which, as the name implies, calculates the average annual emissions only for load-following power plants and the "average marginal", which uses a load-duration curve to calculate the weighted average emissions of power plants that are on the margin for specific time periods. Both these methods are considered to be less-data intensive and therefore can only provide a generic estimate. However, given the data restrictions and time constraints, it was felt that they provided a high enough level of accuracy for the evaluation of the power plant in question.

7.7.3.1 Calculating the annual emission factors

In order to be able to calculate the OM emission factor, irrespective of the method used, it is necessary to have a list of the emission factors for the different types of power plants that provide electricity to the Grid. Without this, it would be impossible to then estimate the displaced emissions. There is however, only a broad consensus as to what are exactly the emission rates associated with different power plant types. The situation is complicated further by the fact that most sources do not clearly show the boundaries of their assessments. This is important especially for power sources that do emit negligible carbon dioxide during their operation, but have emissions associated with the life cycle operations of the fuel cycle (a prime example being renewables and nuclear power). Several sources were reviewed in this work (Parliamentary Office of Science and Technology 2006, Killip & ECI 2005, DTI 2006a, Bettle, Pout, & Hitchin 2006) and a summary of their proposed carbon emissions can be seen in Appendix D. However, in this work the emissions factors from (Bettle, Pout, & Hitchin 2006) have been utilised and adapted, as they are based on a synthesis of primary resources (mainly the Digest of UK energy statistics and the National Atmospheric Emission Inventory data), and were therefore deemed defensible. The emissions factors used can be seen in Table 7.29 below and diagrammatically in Figure 7.27:

Plant type	tC/MWh	gCO_2/kWh
Small coal	0.27	990.9
Medium coal	0.25	917.5
Large coal	0.24	880.8
Oil	0.22	807.4
OCGT	0.25	917.5
Gas	0.15	550.5
Coal/gas	0.22	807.4
Coal/oil	0.24	880.8
CCGT	0.12	440.4
Nuclear, pumped hydro & external sources (wind, wave, solar etc)	0	0

Table 7.29 Carbon emissions for each type of generating plant

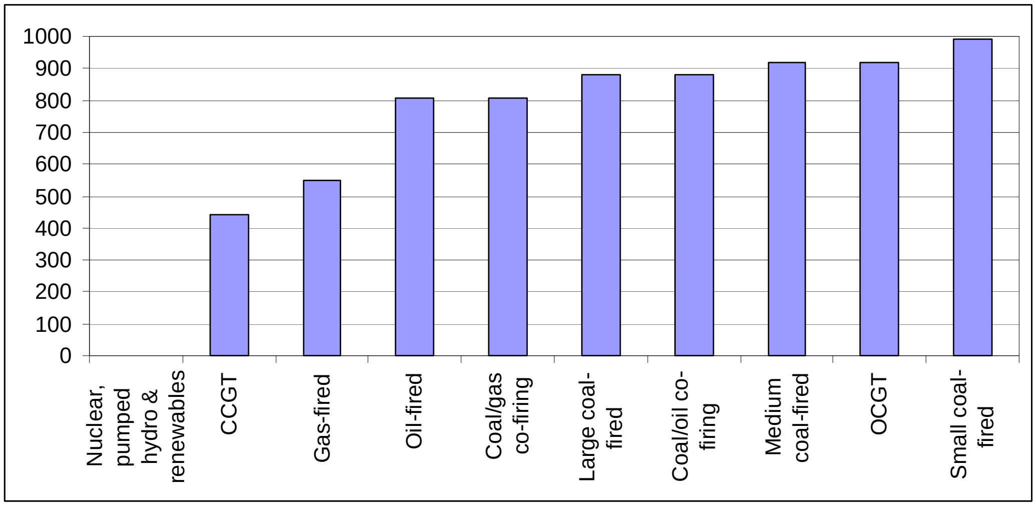

Figure 7.27 Carbon dioxide emissions factors for different power plants

7.7.3.2 Calculation of OM emission factor using the "Average Load-Following" procedure

This method allows the use of aggregated data by power plant type and therefore avoids the need for detailed operational information for each operational facility. The method is based on the ranking of the different facilities by average cost of generation or capacity factor and the calculation of the average emissions associated with the top-third of the power plants (i.e. the one's with lowest capacity factor, or lowest cost). However, due to the nature of the U.K. electricity trading arrangements, the operating costs of all facilities providing electricity are not publicly available, as they are protected by commercial interests. As such, the approach based on average capacity factor has been used in this work to rank the different power plant types operating on the U.K. electricity grid. As such, it was felt that the capacity factor would provide an adequate indication of power plant dispatch order as it was assumed that a low capacity factor would indicate that a power plant type was utilised less and therefore more likely to be at the "operating margin".

The first step in this method is to establish the capacity factors of the different plant types. In order to do this, information was gathered about the installed capacity of the various plant types and their total generation for 2006. Both pieces of information were taken from DUKES (DTI 2007a) (Tables 5.6 and 5.7). However, due to the fragmented nature of the information and the differences in the categorisation of the data between tables, the data had to be manipulated so as to provide the uniform structure required for this evaluation. During this manipulation, however, a certain level of pragmatic assumptions were required. This occurred because many of the data sets provided, were not transparent enough to allow for complete clarity during the segregation of power plant operational characteristics into groups.

The summary table for U.K. power plants grouped into groups depending on their fuel type is given in Table 7.30., while a more complete table in Appendix D provides an analytical breakdown using the DUKES data.

All generating power plants	**Installed Capacity MW**	**Generation GWh**	**Calculated Capacity Factor**		
Total capacity (incl. Imports)	**84,641**	**390,041**	**52.6%**		
Of which:					
Conventional steam stations *(total)*	**38,294**	**168,980**	**50.4%**	**Normalised GW**	**Ranking**
Coal-fired	24,678r	142,681	66.0%	16.3	**2**
Oil fired	4,299r	4,271	11.3%	0.5	**10**
Mixed or dual fired	8,913r	22,028	28.2%	2.5	**7**
Gas turbines and oil engines					
Combined Heat and Power (CHP)	**404r**	**1,954**	**55.2%**	0.2	**4**
Combined Cycle gas turbine stations (CCGT)	**27,059**	**127,055**	**53.6%**	14.5	**5**
Nuclear stations	**10,969**	**69,237**	**72.1%**	7.9	**1**
Hydro-electric stations (total):	**4,150**	**8,301**	**22.8%**		
Natural flow	1,294	4,579	36.7%	0.5	**6**
Hydro-electric stations (natural flow)	130				
Pumped storage	2,726	3,722	15.6%	0.4	**9**
Renewables (other than hydro)	**2,169r**	**4,232**	**22.3%**	0.5	**8**
Imports	**2,000**	**10,282**	**58.7%**	1.2	**3**
			Total	**44.5**	

Table 7.30 Calculation of capacity factor for power plant types for 2006

The following table (Table 7.31) shows the above information condensed and ranked according to the criteria outlined previously, from highest capacity factor to lowest. It must be noted that the guidelines for the calculation of the avoided emissions specify that intermittent/non-firm power sources such as wind/hydro should be excluded from the ranking since they do not provide dispatchable power and therefore cannot be displaced at the margin. In other words, the fact that they have a low capacity factor does not signify that they are being utilised as a “quick response” load-following power plant.

Power plant type	MW	GWh	% of total generation	Capacity factor	Normalised GW	% of total generation (excl. non-firm)	Percentage of top 1/3rd
Nuclear stations	10,969	69,237	17.75%	72.06%	7.9	18.16%	
Coal-fired	24,678	142,681	36.58%	66.00%	16.3	37.43%	
Interconnector	2,000	10,282	2.64%	58.69%	1.2	2.70%	
Combined Heat and Power stations	404	1,954	0.50%	55.2%	0.2	0.51%	
Combined cycle gas turbine stations	27,059	127,055	32.57%	53.60%	14.5	33.33%	76.38%
Hydro-electric stations: nat. flow	1,424	4,579	1.17%	36.70%	0.5	n/a	n/a
Gas turbines/oil engines/mixed use	8,913	22,028	5.65%	28.21%	2.5	5.78%	17.33%
Renewables other than hydro	2,169	4,232	1.09%	22.28%	0.5	n/a	n/a
Pumped storage	2,726	3,722	0.95%	15.59%	0.4	0.98%	2.93%
Oil fired power stations	4,299	4,271	1.10%	11.34%	0.5	1.12%	3.36%

Table.7.31 Ranking and generation fractions for different power plant types

From Table 7.30, it was given that the total generation for 2006 was 390,041 GWh, which once non-firm intermittent generation is deducted, leaves the figure of 381,230 GWh. A third of that total is then 127,077 GWh. Using this as the boundary condition, the top third will include all the generation from the oil-fired, pumped hydro, gas turbines/oil engines/mixed use and part of the generation from CCGT power plants.Renewables and natural-flow hydro are excluded from the assessment, as they are classed as "intermittent" since they are not dispatachable. The percentage contributions of the different power plants in the top third of the ranking can be seen in the last column of Table 7.31.

With this information it was then possible to estimate the OM emission factor for the "average load-following" procedure. The emission factors of the different power plants (previously described in Table 7.29) were weighted by the percentage contributions of each power plant to the top third, i.e. the power plants that are considered to be at the margin, according to the formula below:

$$Operating\ Margin\ emission\ factor = \sum_{i=1}^{n} (EF_i \times k_i) \qquad (7.5)$$

where:

- EF_i is the carbon dioxide emission factor for each type of power plant i
- k_i the percentage contribution of each power plant type to the total top 3rd of generation
- n is the total number of power plant types included in the top 3rd ranking

An important point that needs to be noted is that due to the ambiguity of the contributions to the category "gas turbines/oil engines/mixed use" in the above table, as well as the emission factors that should be attributed to this category, the emission factor was based on the assumption on an even split between the emission factors for OCGT and oil-fired stations. It was felt that this provided a conservative estimate for the assessment.

The emission factor for the Operating Margin, using the "average load-following" procedure, was then estimated to be:

Operating Margin emissions factor **490.7 gCO_2 / kWh**

7.5.3.3 Calculation of OM emission factor using the "Marginal Average" procedure

This procedure calculates the OM emission factor by averaging the emissions factors of the different power plant types, weighted by the total amount of the each power plant type provides power at the margin. The period that each plant type remains at the margin is calculated using a load-duration curve, which shows the types of power plants that were required to meet peak system demand over a specific time period (usually taken to be 1 year or 8760 hours) (World Resources Institute & Broekhoff 2007). More specifically, a load duration curve illustrates demand in descending order rather than chronologically. The height of each slice is a measure of capacity, and the width of each slice is a measure of the utilization rate or capacity factor, meaning that the area under the graph is a measure of electrical energy (i.e. GWh or multiples). The load duration curve for the period of 2006/7 was taken from the (National Grid plc. 2007) and adapted to different axes (the original graph and the variations can be seen in Appendix D), as required in this research. As the detailed data behind the graph was not freely available, a 3rd order polynomial equation was used to simulate the curve, in order to be able to estimate the time spent on the margin for the different power plants.

Using the same ranking as that outlined in Table 7.30 in the previous section, the power stations types were ranked based on their estimated capacity factor. Using the approximation of the load power curve and the data on the operational output of each power type again from Table 7.31 it then was possible to calculate how many hours each plant type operated at the margin. A visual representation of how each type of power plant intersects the load duration curve for the period 2006/7 can be seen in Figure 7.28.

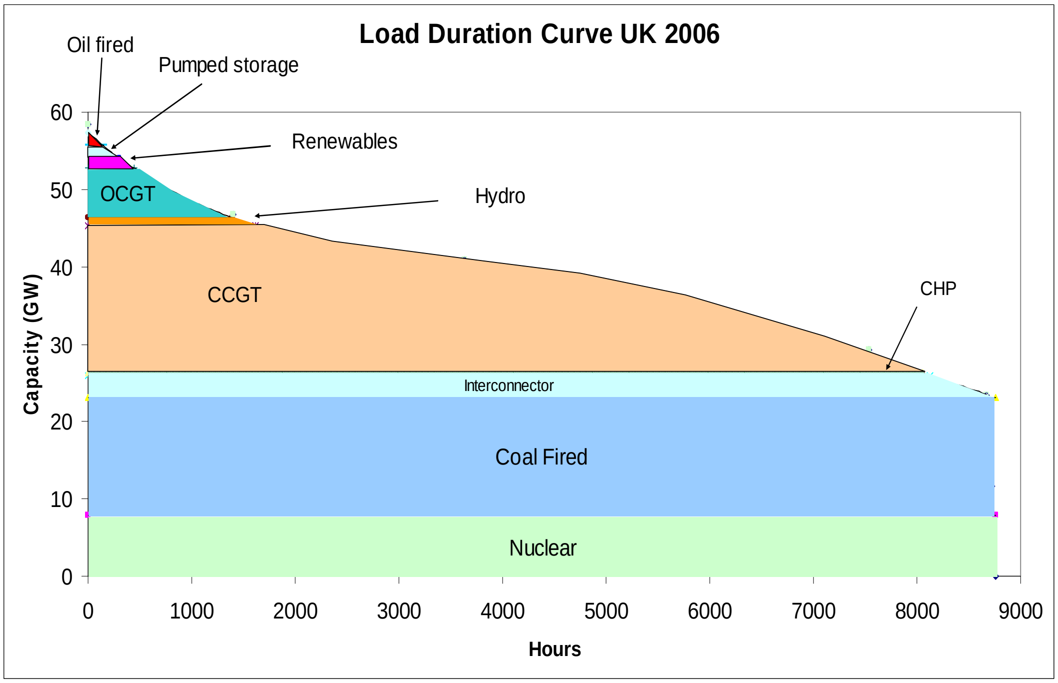

Figure 7.28 Load duration curve with generation per plant type for 2006/2007 in the U.K.

Using the data time periods spent generating at the margin, the Operating Margin's emissions factor, using the "average marginal" procedure, was estimated to be:

Operating Margin emissions factor **482.3 gCO_2 / kWh**

7.5.3.4 Operating Margin emission factor used in this work

A comparison of the results of the two procedures used to estimate the OM emissions factor, indicates that the "marginal average" approach produces a lower estimate than the "average load following" method. Although the former is more analytical in nature, it also by virtue of a lack of detailed information, estimated using approximations. This has as a result the introduction of truncation errors which cannot easily be addressed without better quality data or more precise mathematical formulas, both of which could not be enhanced within the scope and timeframe of this research. On the other hand, the "average load following" approach provides a more coarse, but also less- error procedure as it is based on less assumptions. This leads to the conclusion that this approach represented a more conservative estimate of the OM emissions factor and was thus chosen for this research.

7.5.4 Estimating Baseline Avoided Emissions

With both the Built Margin and Operating Margin emission factors estimated from the above procedures, the estimation of the combined emissions factor for the avoided emissions was achieved with the incorporation of the values into Equation 3.10.

$$EF_{baseline} = w \times EF_{BM} + (1 - w) \times EF_{OM} \qquad (3.10)$$

where

- EF_{BM} is the carbon dioxide emissions factor for the Built Margin,
- EF_{OM} is the carbon dioxide emissions factor for the Operating Margin and
- w is the weighting of the BM.

A brief summary of the estimated emissions factors is again presented in Table 7.32. For the BM emissions factor, a further breakdown into the two categories used to estimate this factor ("currently operating" facilities and "recently consented to" facilities) is also presented.

OM emissions factor (*EF_{OM}*)	**491**	**gCO_2/kWh**
BM emissions factor (*EF_{BM}*)	**495**	**gCO_2/kWh**
Current	*551*	
Projected	*440*	

Table 7.32 Summary of estimated CO_2 emissions factors

The different weighting factors chosen for the wind farms and the nuclear power plant meant that each case had to be calculated separately.

Nuclear Power

From Section 6.7.1, the value of the weighting factor w was taken to be 1, in other words the nuclear power plant was assumed to affect on the Built Margin. This meant that the nuclear power plant's avoided emissions factor is equal to the BM emissions factor

$$EF_{NPP} = EF_{BM} = 495\ gCO_2/kWh$$

Wind Power

For both onshore and offshore wind power, it was assumed that there was an equal weighting between the effect on the Built and Operating Margins (w = 5). The end result of this assumption meant that the Avoided Carbon Dioxide Emissions Factor for the wind farm is:

$$EF_{WP} = 0.5 \times EF_{BM} + (1 - 0.5) \times EF_{OM} = 493\ gCO_2/kWh$$

Table 7.33. shows the summary of avoided carbon dioxide emissions factors for both technologies

Avoided CO_2 emissions factors		
Wind Farms	493.0	gCO_2/kWh
Nuclear Power Plant	495.2	gCO_2/kWh

Table 7.33 Avoided emissions factors for wind and nuclear power

With the above values and the already calculated lifetime electrical generation for each power plant the total avoided emissions, over the lifetime of operation, were calculated. The avoided emissions do not include transmission and distribution losses just the actual avoided carbon dioxide emissions from electricity generation:

Displaced CO_2 emissions from lifetime *operation*		
Nuclear Power Plant	240,569,262	tonnes CO_2
Onshore Wind Farm	10,186,514	tonnes CO_2
Offshore Wind Farm	34,676,324	tonnes CO_2

Table 7.34 Total quantities of avoided CO_2 emissions from operational stage

From a full life cycle perspective however it is necessary to balance these avoided CO_2 emissions against the emissions generated during the full life cycle for each technology. To this aim, the emissions previously estimated for each technology were recalculated so that they represented *only* the carbon dioxide emissions and not the CO_2 equivalent emissions. These values were deducted from the values in Table 7.33 to provide the Net Avoided CO_2 emissions factors (see Table 7.35. below).

	Avoided CO_2 emissions factors	Lifecycle CO_2 emissions per kWh_e	**Net Avoided CO_2 emissions factors**	Units
Nuclear Power Plant	495.2	7.61	**487.6**	gCO_2/kWh
Onshore Wind Farm	493.0	8.55	**484.5**	gCO_2/kWh
Offshore Wind Farm	493.0	13.11	**479.9**	gCO_2/kWh

Table 7.35 Life cycle Carbon Dioxide emissions per kWh

Using these Net avoided emissions factors, the Net displaced carbon dioxide emissions were calculated, and displayed analytically in Table 7.36.

Net displaced CO_2 emissions from the *whole lifecycle* over lifetime of operation		
Nuclear Power Plant	236,872,307	tonnes CO_2
Onshore Wind Farm	10,009,851	tonnes CO_2
Offshore Wind Farm	33,754,201	tonnes CO_2

Table 7.36 Net avoided CO_2 emissions from the three lifecycle

These values represent the clear environmental benefit from connecting one of the three technologies to the electricity grid, as they take into account the whole lifecycle not just the point of electricity generation. A more visually representative illustration of the values in Table 7.35 can be seen below, in Figure 7.28.

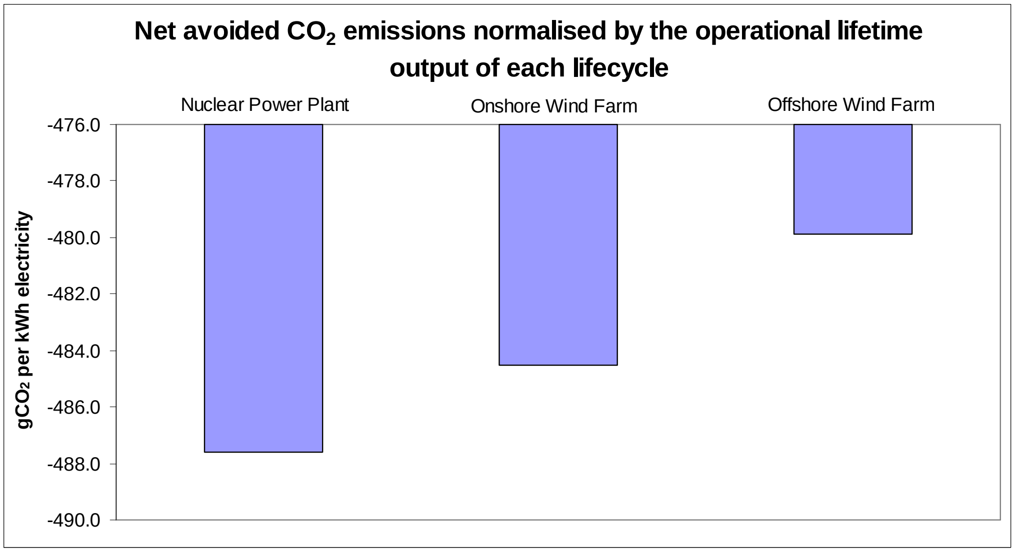

Figure 7.29 Net avoided lifetime CO$_2$ emissions per kWh electricity from the three lifecycles

7.5.5 Carbon Dioxide Gain Ratio (CDGR)

The Carbon Dioxide Gain Ratio demonstrates the number of times the avoided carbon dioxide emissions from the operation of the energy supply technology exceed the quantity of emissions resulting from the operation of the lifecycle.

$$CDGR_{nuclear} = \frac{240,569,262}{3,164,423} = 76.0$$

$$CDGR_{onshore\ wind} = \frac{10,186,514}{151,746} = 67.1$$

$$CDGR_{offshore\ wind} = \frac{34,676,324}{789,653} = 43.9$$

From these ratios, it is clear that the nuclear fuel cycle has the best ratio of avoided to embodied emissions, followed by onshore wind and finally offshore wind.

7.5.6 Carbon Dioxide Payback Period (CDPP)

Based on the definition given in the methodology chapter, the time required for each power plant to pay-off their lifecycle embodied emission was calculated.

$$CDPP_{nuclear} = \frac{3,164,423}{3,947,872} = 0.80\ years$$

$$CDPP_{onshore\ wind} = \frac{151,746}{404,394} = 0.38\ years$$

$$CDPP_{offshore\ wind} = \frac{789,653}{1,350,168} = 0.58\ years$$

From the above values, it can be said that the onshore wind farm pays back its embodied emissions the fastest, followed by offshore wind and finally the nuclear

8. Discussion of Results

8.1 Introduction

The previous chapters of this thesis have dealt with the calculation and assessment of the parameters originally defined in this study. In this chapter these results are drawn together into an overarching discussion of their implications with regards to the questions set out at the beginning of this work. The discussion presented in this chapter is further surpported by a section covering further implications of utilising wind or nuclear power that are not directly assessed in this work. As such, the purpose of this section is to present a more complete assessment of the research questions within a wider context. The inclusion of this Chapter also helps in the transition from the findings of the current work to the identification of issues that should be addressed by any subsequent studies in this area of research.

8.2 Energetic Indicators

This section describes the implications that arise from the comparison of the results relating to the energetic indicators used in this study. Thus, the outcome of the comparisons of Cumulative Energy Demand, Energy Gain Ratio and Energy Payback Period are discussed in detail below.

8.2.1 Implications of CED results

As stated previously, the parameter of Cumulative Energy Demand is an indicator of the total primary energy requirements for a given system or product. In essence, the CED represents the level of depletion of available energy sources in general, and thus by default, also of the depletion of finite fossil fuels. From the summary in Section 7.4.3, it was seen that the nuclear power lifecycle exhibits the highest CED of the three technologies investigated, followed by offshore and, finally, onshore wind.

It has been argued that the CED of an energy supply system can be used as an initial indication of a system's environmental performance (Huijbregts et al. 2006). This is mainly due to the fact that, currently, primary energy inputs are still based heavily on fossil fuel consumption, which in turn has been linked with the phenomenon of Climate Change. As such, it could be argued that since nuclear power has the highest CED, it can also be said to have the highest environmental impact. However, this conclusion needs to be tempered by the fact that the electricity produced from the three energy supply systems under consideration here is not directly reliant on the burning of fossil fuels (i.e. the direct fuel input to the lifecycles is not a fossil fuel). As a result of this, the correlation between CED and other environmental impacts for nuclear and wind power is less direct than for other energy supply systems, such as a coal-fired power plant.

From the point of view of sustainability, it can be argued that a higher CED implicitly suggests a higher strain on available and limited energy resources. This would then indicate that the nuclear power lifecycle places more significant burdens on these resources than the wind power. Subsequently, in a theoretical situation where a significant reduction in the available resources could be envisioned, nuclear power would appear to be a less sound investment for electricity generation. This conclusion is intrinsically tied to the fact that for wind power, the CED of the lifecycle is almost independent of the electricity produced, i.e. the CED of the wind farm remains almost unaltered by the amount of actual electrical generation and is only affected indirectly by ‘second order’ inputs such as maintenance requirements. In the case of nuclear power however, the CED of the fuel cycle is influenced by the electrical output since this in turn dictates the uranium ore requirements (loosely, it could be said that larger electrical output from the nuclear power station will result in higher uranium requirements). This can be seen diagrammatically in Figure 8.1 below:

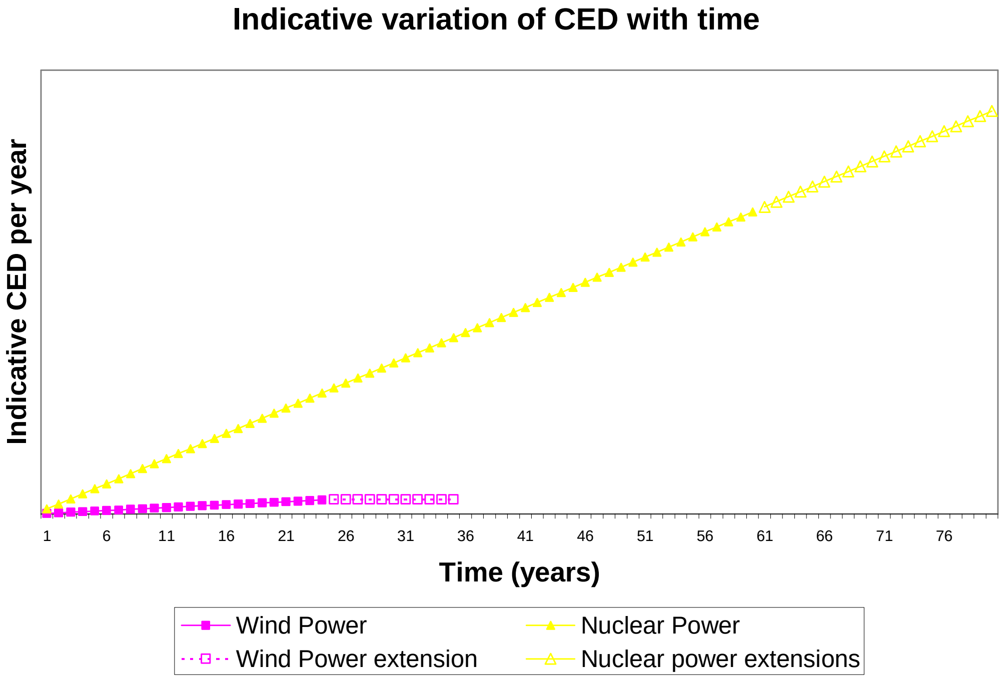

Figure 8.1 Variation of CED with time (indicative)

It is important to note however that the absolute value of the CED as described above is of relatively limited value in the comparison undertaken here. This can be changed though once the CEDs of the three systems are divided by their useful electricity production, as demonstrated in Section 7.2.1.3. By implementing this normalisation the CED can become a basis for comparison for different systems, even when these are based on completely different operating characteristics. This is possible because the normalised values relate the CED to the useful product of the system (which is the same in all cases, i.e. electricity). When this step is taken the relative positions of each technology are reversed, positioning nuclear power as the most preferred technology and offshore wind as the least efficient version, from a purely energetic perspective. As a result it is maintained here that the definition of a normalised CED is a better indicator for comparison of energy systems, as it provides a common point of reference, which is the useful product, electricity. From this point of view, the nuclear fuel cycle might have larger energy requirements, but also provides more useful product. The balance is tipped again however in favour of renewables when it is considered that the CED per kWh of wind power will continue to decrease, the longer the system produces electricity. The same however is not the case for nuclear, as the operational energy requirements will always necessitate an energy input to produce an electrical output. This fact is demonstrated qualitatively in Figure 8.2:

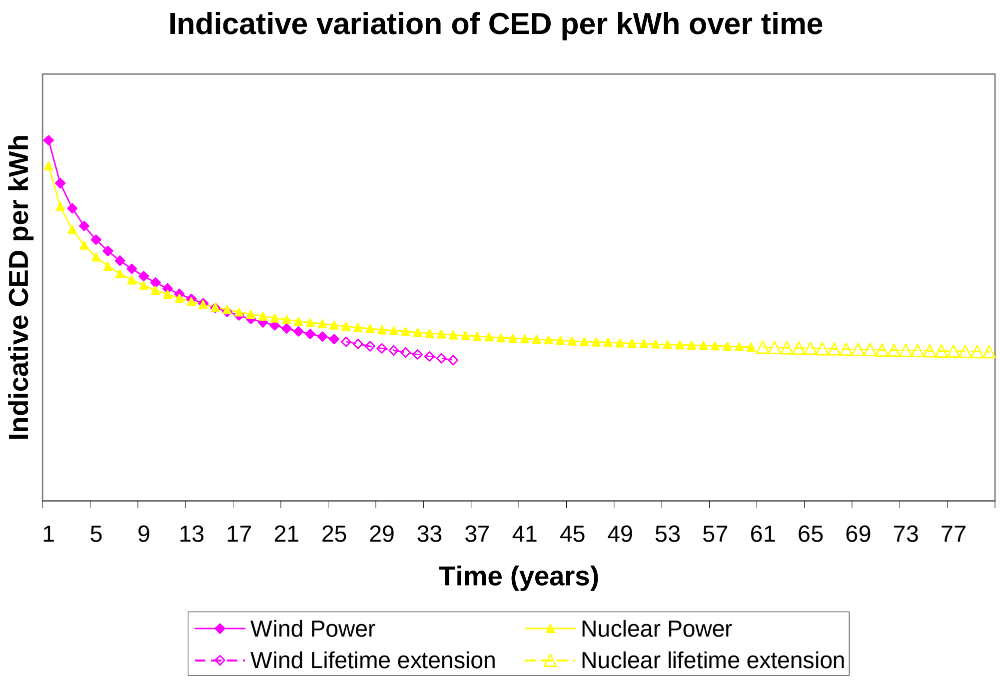

Figure 8.2 Variation of normalised power plant CED over time

From Figure 8.2, it can be seen that once the wind power lifecycle pays off its initial energy inputs (CED; in the form of power plant construction energy requirements), as its fuel source is "free", it will continue producing electricity without any further major energetic input (within the confines of a realistic extension of the wind farm's operational lifetime). Thus its CED per kWh produced will continue to decrease. The nuclear lifecycle on the other hand can only ever break even with its continuing operational inputs, i.e. as it requires continuous energetic inputs for fuel fabrication and waste management, once it pays back the capital energy (for construction of power plant etc), it will still have an continuing input (in the form of energy for fuel fabrication) that will never cease to be required as long as the plant operates.

In effect, this conclusion can be traced back to the fundamental difference between the nuclear and renewable fuel cycles, namely the fact that the nuclear fuel cycle is dependent on a fuel source that is not renewable and requires processing, whereas wind power is dependent on a non-depletable resource that requires no processing.

Apart from the importance of the variation of the cumulative energy demand per unit electricity over the operational lifetime (and especially if this is extended), there is also the issue of the total energy requirements required by each system, independently of any normalization. Thus it can be argued that, despite the fact that wind power would have higher energy demands per unit of electricity than nuclear power (as per the results presented in Figure 7.8 in Section 7.2.1.3), the simple fact of not being able to afford the capital energy outlay of the nuclear system (i.e. the higher CED) would mean that wind power would offer the better option, as it has a lower absolute lifecycle CED. This in effect means that wind power places less strain on the background system providing the energy inputs. A parallel of this can be seen in the financial world, where a project may provide higher rates of return on investment than the next option but the prohibitive capital costs of the first would make the latter the only possible option. This however is a secondary point and only becomes a real deciding factor when the normalized CED requirements of the systems being compared are very similar, as in the case of nuclear power and onshore wind (but not as applicable in the comparison of the nuclear power plant and the offshore wind farm).

It is also supported in this work that studies that do not discuss the results of Cumulative Energy Demand per kWh provide an incomplete assessment of the energy systems they are discussing. However it is also vital to note that a static treatment of this parameter is also detrimental to understanding, especially where the variation of the values under comparison do not remain the same.

8.2.2 Implications of the Comparison of EGR and EPP

Two of the main indicators under investigation from the point of Net Energy Analysis, are the Energy Gain Ratio and Energy Payback Period. As previously discussed, the EGR can be thought of as an indication of how much more energy is produced by an energy supply system when compared to the energy inputs to the system, while the EPP describes how long it takes for the system to pay back, in energy terms, the inputs invested in that system.

It has been argued that the development of human society has been based on the utilisation of energy sources with increasing EGRs (Gagnon). As a result, alternative (i.e. renewable and nuclear) energy technologies will need to have a comparable if not higher EGR ratio than the current conventional (i.e. fossil fuel based) system (Roberts 2006). A corollary of this is that, if there is a shift to energy supply systems with lower EGRs , then this will effectively mean that more of nature's and society's productive resources will need to be sequestered to produce the same amount of energy. Thus, laying aside the potential beneficial effects of increased energy efficiency, with resources redirected to electricity generation, there will be fewer resources available for non-electricity generating activities. It has also been argued that assuming that the EGRs for alternative technologies are indeed low, then it is unlikely that these technologies can effect a reduction of emissions if the technologies themselves require large energy inputs. Ultimately, a negative feedback loop could be envisaged where energy supply systems with low EGRs acts as inputs to other systems with even lower EGRs leading to Energy Gain Rations below unity (Gagnon). Thus, the EGR is a fundamental parameter in the assessment of any energy supply system, if not for the technology itself, then for the system that it integrates into.

Based on the above premise, it is desirable that energy supply systems have as high an EGR as possible. From the results produced in this study (seen in Table 7.1 in Chapter 7), it can be seen that nuclear power has the highest EGR, followed by onshore wind and then by offshore wind which has an EGR almost half that of nuclear power. This would mean that nuclear power represents the best option as it is the most efficient converter of primary energy inputs into electricity. When however the "opportunity cost" convention is applied (i.e. the renewable sources are "credited" for the quantity of depletable fuels they avoid using to generate their electricity) then the situation is reversed. In this case onshore wind becomes the best option, followed by offshore wind, while nuclear to which this convention is not applicable, comes in at third place. It should be noted that the "opportunity cost" convention could be applied to nuclear power, depending on the exact definition of the terms. It has been argued in other works that since nuclear power does avoid the depletion of depletable *fossil* fuels while, at the same time uranium has no other major use, nuclear power should be eligible for the use of the "opportunity" cost (WNA 2005a). While both these arguments are valid, it is felt by the author that the opportunity cost should be strictly applied to the avoidance of the depletion of any *non-renewable energy source*, irrespective of whether humanity has yet found another use (as in the case of uranium) for it or not. As such, since the extraction of uranium cannot ultimately be seen as sustainable, it is argued that the "opportunity" cost should not been applied to nuclear power.

Ultimately, the comparison of nuclear and wind power with regards to their EGR, becomes a question of the conventions applied to the analysis. Depending on the definition of sustainability used, either technology can be found to be the best option. Irrespective of the definition used however it is clear that both types of energy supply systems are net energy producers and therefore have something to offer to the overall energy system they are integrated into.

Another complementary indicator to the EGR ratio in a Net Energy Assessment is the Energy Payback Ratio (EPP). In many ways, the EPP is a better indicator of energy efficiency, as it is not related to the operational lifetime of the power plant, and hence provides a better indication of the rate of energy delivery. The EPP also addresses the question of whether an energy supply system can pay back its capital investments within its operational lifetime. Looking at the EPP for the three technologies under investigation in this work, it becomes obvious that, all three systems pay back their energy investments, well within their operational lifetimes. It is interesting to note that wind power that has historically been criticised for never paying back the energy inputs to the lifecycle (as highlighted and discussed in (Milborrow 1998), actually performs better in this respect than nuclear power. In reality, the fact that nuclear power has a longer EPP despite having a better EGR than wind can be attributed to the high up-front energy expenditures, as well as to the fact that "Back End" operations are a significant percentage of the lifetime energy inputs. This is not the case with wind however giving these technologies the lead with respect to payback times.

An important issue that has not received enough attention in work to date is that concerning the parasitic consumptions of electronic components in wind turbines. It is clear that due to the electronics required to control the operation of a wind farm, certain levels of power are required, irrespective of whether the farm itself is actually producing electricity at any given point or not. The levels of this consumption however are not clear and therefore it has been suggested that it could be significant. If this were the case then this naturally would alter the lifecycle energetic performance of the wind turbines as well as affect their emissions reduction potential. Obviously, if a wind turbine is using Grid-supplied electricity in 'stand-by' mode (i.e. not generating), then it should be included in the electrical inputs required for operation. In general, there is a dearth of information on this matter, with the general consensus being that wind turbines consume insignificant amounts of electricity. This assumption has been used in this work as well, but it is important that the matter is looked into more thoroughly once data becomes available. It is important to note that all power plants (including nuclear power plants) have a parasitic consumption. The reason however this is raised as an issue for wind power but not for other forms of electricity generation is that wind power (and renewables in general) are conceived as operating close to their energetic “break-even” point (i.e. in very extreme cases they might consume as much energy or even more than they produce).

8.3 Greenhouse Gas Emissions Indicators

As stated throughout this work, the drive to reduce GHG emissions is seen as one of the most difficult challenges facing the energy supply sector and, given the intricate connection between human development and energy use, humanity in general. One of the main avenues on this path to “decarbonising” electricity generation is the adoption of energy supply systems which have the lowest possible emissions per unit of electricity produced. However, it is important to assess technologies on a whole lifecycle basis as even technologies (such as wind and nuclear) that do not emit GHG at the point of electricity generation still have emissions associated with other stages in the lifecycle. This has been demonstrated by the results of this work and illustrates that while both types of energy supply system have very low emissions per kWh, these are not zero. A comparison of the results for the two wind farms (onshore and offshore) and the nuclear power plant shows that for the baseline assumptions, nuclear power actually performs better than wind power. Nuclear power’s associated emissions are almost half those associated with both onshore and offshore wind. However, it is very important to note that despite this difference between the normalised emissions, both systems generate emissions levels an order magnitude lower that the nearest conventional generator. Thus from a system perspective, it could be argued that both types of energy supply systems are suitable choices in the road to creating a ‘low carbon’ economy. Furthermore the associated emissions with each technology are dependent on the background system as much as on the process requirements during each lifecycle. Hence, although for conditions that reflect the current and near term U.K. situation nuclear power emits lower levels of GHGs, it is conceivable that for any change of the underlying system, the relative ranking of the energy supply systems might also be affected. A corollary of this is that for other conditions pertaining to other country-specific situations, the current results might vary. As a result of this it is felt by the author that the difference in emissions between the two types of plant is not substantial enough to be used as the sole basis for arguing for the adoption of one technology over the other.

8.4 Issues raised by the parametric analysis

Further insight into the implications of the results of each system’s performance is provided by the results of the parametric analysis for the Energy Gain Ratio, the Energy Payback Period and the normalised GHG emissions from each lifecycle. The results of the parametric analyses are discussed per technology, as this allows for a deeper focus on the intricacies of adopting the different energy supply systems.

8.4.1 Nuclear power

One of the major findings of the parametric analysis is the effect that different ore grades have on the lifecycle. One of the main arguments levelled against the nuclear fuel cycle (by researchers such as Storm van Leeuwen et al (Jan Willem Storm van Leeuwen & Philip Smith 2005)) has been that for low grade ores, the lifecycle energy gain ratio drops below one (i.e. the technology consumes more energy than it produces) and that the emissions rise to levels similar to those of current conventional (i.e. fossil fuel fired) generation. In order to investigate these claims, the effects of changing the mine supplying the uranium ore requirements were modelled using the models created in this study. From the results, it can clearly be seen that although different ore grades affect the three main parameters of this study, even for the lowest ore grades (whether it is the Rössing or Olympic Dam mine), the emissions only increase by 30%, while the EGR is reduced by approximately 20%. In other words, while it is obvious that ore grades affect the lifecycle performance, for the given parameters and assumptions, they do not effect the changes claimed by Storm van Leeuwen et al. Similar conclusions were also reached by British Energy in their EPD of the Torness nuclear power station(AEA Technology & British Energy 2006), by the Integrated Sustainability Analysis group in Australia (ISA 2006) and by Dones et al (Dones 2007). An interesting point to note is illustrated by the comparison of the results for Rössing and Olympic Dam; although both mines have quite similar ore grades, the better energy performance of the Rössing mine (i.e. primary energy requirements for ore extraction) means that it has significantly less negative effects on the nuclear power lifecycle, when supplying the required uranium ore. This indicates that it is not only the ore grades that affect the lifecycle performance per se, but also the energy inputs that help provide the ore in the first place. A direct result of this conclusion is that if the energy required for mining and processing the ore comes from low/near-zero carbon emitting sources (i.e. renewables), then a lower ore grade need not necessarily imply an increase in associated emissions. Therefore, given the timeframes associated with the nuclear fuel cycle and the current impetus to de-carbonising the economy, it should not be taken for granted that a decline of ore grades will necessitate an unexpected rise in the nuclear fuel cycle emissions. These points highlight that the importance of the background system should not be underestimated in the assessment of any energy supply system.

Another very important point to note is the effect that the choice of enrichment method has on the lifecycle results. Even the use of the diffusion process for 30% of the uranium requirements leads to an EGR of less than half that of the baseline scenario, while an ‘all-diffusion’ enrichment process leads to the lowest energetic performance of all the options investigated. As such, it is clear that this parameter is a very important factor in the determination of the energetic impacts of the nuclear fuel cycle. The GHG emissions however are not so dramatically influenced by the different enrichment methods. This can be traced back once again to the background system assumed to be supplying energy and namely the French electricity generation mix. Despite the fact that the diffusion process has energy requirements almost two orders of magnitude higher than those of the centrifuge method, the fact that it has been assumed that the enrichment facility is in France, and hence supplied by a ‘low-carbon’ grid mix (i.e. heavily nuclear power reliant), means that the emissions do not rise by the same percentage as the energy inputs do.

The results of varying the tails and product assays from centrifuge enrichment conform to expectations, i.e. that an increase in product enrichment leads to an increase in energy use and hence lowers the EGR and increases the EPP as well as the associated emissions, and vice versa. The same holds true for the tails assays, as an increase in the “waste” enrichment levels has a detrimental effect on both the energetic and emissions indicators and vice versa.

Another parameter that has been highlighted as important in the assessment of the nuclear power lifecycle is that of the nuclear fuel burn-up rates. Recently, there has been an emphasis on the increase of burn rates, as this then has a beneficiary effect on the financial balance of the power station, as it means lower uranium requirements. As such, burn-up rates of up to 60 GWd/tU are being envisaged for the next generation of nuclear reactors. At the same time, current burn rates in the U.K. are much lower than the ones claimed for future reactors. The analysis shows that the higher burn-up rate can have a positive impact on the energetic and emissions indicators. However, as pointed out by Richards (Richards 2008), certain issues emerge from the use of higher burn-up rates:

- Higher burn-up rates results in spent fuel with higher levels of radioactivity and with diminished cladding. This results in the need for different storage solutions than those applicable to the current “legacy wastes” created by older reactor types with lower burn-up rates.
- It is not clear whether the effects of increased burn-up have been properly assessed by U.K. government agencies in their modelling of the ‘Back End’ of the nuclear fuel cycle. As such, it is also likely that the modelling used in this research would need to be modified to take into account the increased levels of radioactivity. These would then require more shielding or different disposal procedures as well as increased monitoring and cooling requirements, all of which would ultimately affect the results of the nuclear fuel cycle.
- The use of higher burn-up rates reduces the levels of plutonium in the Spent Fuel, making current policies of reprocessing non applicable. Whereas this might be an advantage from the point of view of nuclear proliferation security (nuclear waste from reprocessing has been highlighted as one of the main sources of radioactive materials that could be used in nuclear terrorism (Campaign for nuclear disarmament 2006b)), the lack of plutonium, in effect, excludes the possibility of using breeder reactors. Fast Breeder reactors have been hailed by some commentators as the solution to making the nuclear fuel cycle sustainable, as they are meant to produce new fissionable material at a greater rate than they consume, through the conversion of certain types of radioactive elements into other radioactive forms. With the reduction of plutonium from Spent Fuel however this becomes less likely to be an option.

As a result, whereas higher burn-up rates do lead to better lifecycle performance for the given assumptions, the uncertainties surrounding the ‘Back End’ implications of this parameter would require further investigations.

Varying the load factor and the operational lifetime of the nuclear power plant also impact the lifecycle performance. As can be expected, a reduction in the lifetime operation of the station or of its load factor will lead to higher emissions per kWh and a worse Energy Gain Ratio. This can be traced back to the fact that the energy expenditures for the ‘Front’ and ‘Back End’ of the fuel cycle have to be balanced against the resulting lower electricity output. Thus, although a shorter operational lifetime or a lower load factor would lead to less energy inputs (less fuel requires processing and subsequently less waste management), they cannot counterbalance the reduced electrical output. The Energy Payback Period however is affected inversely by variations in the operational lifetime; that is to say that a reduced operating lifetime actually leads to a better EPP and vice versa. This can be explained simply by the fact that by reducing the lifetime, as previously stated, the energy requirements for fuel processing are reduced. The *annual* electrical output however, remains the same, and therefore lower energy investments are paid back at the same rate, leading to a lower EPP.

From the point of view of the construction of the Nuclear Power Plant, the use of an older "bill of materials" was investigated in the parametric study. As stated in the chapter on the modelling of the nuclear power cycle, there is a lack of accurate and up-to-date information concerning the building materials required for the construction of a modern nuclear power plant. Most data sources are presented in an aggregated form and therefore lack detail, or else are too old to accurately represent current practices. In the Baseline Scenario in this work, the most recent estimates for materials were used. Conversely, the most analytical breakdown of building materials publicly available appears to be for a reactor of early 1970s design. The use of the 1970s design list of materials had approximately a 7% effect on the lifecycle's energetic performance, illustrating the low impact this stage has on the lifecycle.

Finally, an important group of parameters are those related to the "Back End" of the nuclear fuel cycle. Given the uncertainties of this stage of the lifecycle, it was considered important to carry out test by varying some of the more contentious parameters i.e. the operation of the Interim and Final Storage facilities. The original values for the operational lifetimes for the two facilities were taken from previous reports on the subjects from a variety of sources, including governmental reports. The values quoted in those sources have been criticised as overly optimistic by certain detractors (e.g. the aforementioned (Storm van Leeuwen 2007)), especially given the current state of affairs with respect to nuclear waste management.

To reflect these fears, the period of time that the final repository required "active monitoring" was extended by a factor of 10 to 500 years. As would be expected, this had a negative effect on the lifecycle indicators under investigation, by approximately 30%. Other commentators however have been even more optimistic, claiming that by the time the next generation of NPPs are operating, the "Back End" of the fuel cycle will have been streamlined. Thus, the interim storage phase was reduced to 10 years, reflecting the assumption that all nuclear waste would be dealt with immediately and then placed in final storage as soon as practicable. This approach resulted in a marginally positive effect on the lifecycle. Finally a combination of short term interim storage but very long term monitoring in the final repository also resulted in a negative impact of NPP lifecycle assessment.

In another investigation into the "Back End", the effects of incorporating the management of depleted uranium were also researched. This phase of the lifecycle has rarely been included in most assessments of nuclear power and was therefore deemed beneficial to the aims of the parametric analysis. As such, using similar assumption to those of (Jan Willem Storm van Leeuwen & Philip Smith 2005), the inclusion of depleted uranium reprocessing led to a 21% decrease in the EGR and approximately 25% increase in the EPP and lifecycle GHG emissions.

The above variations demonstrate that the uncertainties related to the nuclear fuel cycle can have a significant impact on the lifecycle's performance and should therefore be carefully re-examined when additional information becomes available. At the same time however it appears that claims that any one of the above uncertainties on its own can turn the nuclear power lifecycle into a net energy consumer are unfounded. In the worst case where all the uncertainties are weighted against the nuclear lifecycle's favour, nuclear power still remains a contributor, albeit not as the preferred option from a lifecycle viewpoint.

8.4.2 Wind power

As almost identical parameters were investigated in the analysis of both the onshore and the offshore wind farms, the results can be compared and commented on in parallel.

The first parameter to be investigated for wind power was the effect that different energy yields had on the lifecycle performance of the wind farms. Although the energy yields of both onshore and offshore wind were based on standard wind speed modelling (and in the case of the onshore wind farm, actual measured wind speeds), it was judged appropriate to investigate the effects that an increase or decrease in the assumed yield would have on the performance. This decision was further supported by the discrepancies in the capacity factors quoted by different organisations , for example (Sustainable Development Commission 2005), (BWEA 2006) and (Renewable Energy Foundation & Oswald Consultancy Ltd. 2006). For the onshore wind farm, a 10% variation of energy yield results in a similar variation in the EGR, while the GHG emissions and EPP were affected more by the negative variation in energy yield (-10%) than by the positive variation (+10%) in the parameter. The exact same was true for the offshore wind farm. These results demonstrated the importance of getting accurate wind speed measurements for the wind farm locations, as the wind speed variations caused differences between 11-10% in all lifecycle indicators.

Variations in the wind farms' operational lifetime also had a significant effect on environmental performance. A reduction in the lifetime, reflecting an early decommissioning, had the most severe impact of all the parameters, leading to the lowest EGR and the highest emissions. The positive effect of an increase in the lifetime however, was not of the same magnitude as that caused by the decrease in lifetime, indicating the relative impact and importance of the maintenance requirements (i.e. the longer the lifetime, the more maintenance inputs are required, thus reducing the benefits of increased energy output).

8.5 Net-Energy Density

The indicator of Net-Energy Density can be seen as a measure of the amount of land a given energy supply system needs to produce energy. Thus, when viewed through the lens of ever-decreasing available land and the increase in competition between different land utilizations (i.e. farming, housing, natural conservation) it can be seen as an indication of sustainability of a system. In the past, renewables and especially wind power have been criticised for their land use as they are considered 'diffuse' energy sources that require vast amount of land to produce relatively little energy in return. Similarly, nuclear power has come under fire by environmentalists who perceive the disturbance of land resulting from uranium mining and the deposition of wastes as not worth the energy produced by nuclear power stations. Whereas there are also issues concerning the suitability of land for other uses (i.e. what level of reclamation is achieved), those particular questions have been deemed beyond the scope of this study. The focus has hence been solely on the amount of land that is no longer available for other uses, as it is being utilized then by either nuclear or wind power cycles.

The results of this analysis seem to support the claims that wind power is diffuse and thus its uptake could potentially lead to land utilization conflicts, in a world where available land is considered a scarce resource. This is especially the case for onshore wind, which apart from other issues stemming from public acceptance of the technology will have the added competition for land from other, possibly more lucrative, uses. Such a case could be envisaged under the scenario of an increased government commitment to the use of biofuels. The overall results do not change significantly (in the sense that the relative rankings of the technologies remain unaltered) even when it is assumed that the land-take of the wind farm is restricted to the actual area taken up by the turbines, freeing up other areas for other utilisation. It needs to be noted though that nonetheless there is a significant improvement in the Net-Energy Density of the onshore wind farm through the correct attribution of actual land requisition. With this added realization it is even possible to envisage situations where wind farms coexist with other technologies, e.g. biofuels, thus creating a virtuous cycle renewable energy co-production, while sharing the same resource (i.e. land). The issue of land, or more appropriately surface area, use is deemed less of a critical issue for offshore wind, as there are relatively fewer direct conflicts of ocean utilization. Despite this, it is possible that surface area related problems might appear, depending on the positioning of the wind farm, through competing applications such as fishing, navy and radar exclusion zones, and ocean going traffic routes. Nuclear power on the other hand, has best Net Energy Density of the three systems considered. As in the case of other parameters, this is more due to the large Net Energy of the nuclear power cycle rather than the fact that it requires less land than wind power. The end conclusion of the analysis of this parameter is that, if land use were to become a major contentious issue, all else being equal, nuclear power offers a better solution to providing electricity.

8.6 Water Usage, Material requirements and Resource Depletion

The connection between water usage and electricity generation is rarely considered in the assessment of the sustainability of energy supply systems. However, as discussed in previous sections it is an important factor, especially in the case of conventional generators (i.e. thermoelectric cycles). Investigations into the subject are even less frequent in the case of renewables, since they do not use any water directly in their operation, with the exception of large hydro and some forms of geothermal energy. In the past, nuclear power has been investigated, usually alongside conventional generation, since in effect it is based on a steam cycle just like other fossil fired generators (i.e. coal-fired), but there is generally a lack of results and literature in the field.

Using the same boundary conditions and methods as for the other parameters previously discussed, the analysis has arrived at the surprising result that the nuclear fuel cycle actually uses less water per kWh electricity produced, than the wind power cycle. As stated in the Chapter 7, however, this is once again due to the high electrical output of the nuclear cycle rather than due to a lower absolute water consumption level. This means that this conclusion needs to be appropriately interpreted; while it is true that nuclear power uses less water for a given amount of electricity (and hence could be argued is more efficient), if the scarcity of water is the overriding issue, as might be the case in an arid country with heavy drains on water levels, then it needs to be highlighted that wind power uses less water in total than nuclear power and therefore might be a more appropriate option. It is also important to note that the nuclear fuel cycle uses water as an integral part of its operations, while wind power does not. Within a U.K. context, it could be argued that the results of this parameter are of less immediate importance. Given however that most major international organisations (with a prime example being the IPCC) have highlighted the necessity of safeguarding the planet's freshwater supplies, the importance of water usage should not be underestimated.

The concepts of material requirements for construction and resource depletion are directly related; the major difference is the boundary condition applied to each parameter. The material requirements for construction can be seen as the direct expression of resource depletion during the construction phase (rather than over the whole lifecycle), with the emphasis placed however, on the specific materials. The construction material requirements are more an indicator of the short term effects a building programme might have on the immediate economy (and vice versa); as such it is related to issues of material availability rather than actual scarcity. The results for this indicator show that nuclear power is less of a burden on construction materials than wind power. This would seem to indicate that nuclear power would be less susceptible to material shortages for a given amount of electricity produced. This effect could be especially pronounced in a world where the competition for certain materials, such as steel, between sectors and nations is becoming significant. As with the issue of water however, this conclusion needs to take into account the nature of the use of the material in question. Nuclear power uses a much larger quantity of materials up front but also during operation (i.e. cladding on fuel rods/Spent fuel). Wind power of course does not have this requirement.

When the whole lifecycle is considered, the results for resource scarcity and depletion are harder to draw conclusions from. There is an almost even division in the number of materials affected by each technology, leading to the conclusion that without a clearer weighting it is not possible to establish which technology performs better i.e. has a lower impact on resource depletion. The results are useful nethertheless for future studies, where the relative impacts could be evaluated against specific criteria.

8.7 Avoided emissions

A significant outcome from the results of this study is that of the estimation of the avoided emissions, achieved through the implementation of nuclear and wind power projects. The results presented in Chapter 7 have demonstrated that despite the fact that wind and nuclear are not completely interchangeable (from the perspective of the electricity grid operators), they are both responsible for displacing similar quantities of CO_2 emissions per kWh of electricity produced. The work has also shown that actual displaced emissions factor for both technologies is actually significantly lower than that quoted in literature, and almost half that quoted when it is assumed that coal-fired generation is displaced.

Many proponents of wind power have argued that wind power will displace baseload generation, and therefore the emissions factor should be modelled on that of coal-fired power plants (BWEA 2005). These assumptions were broadly supported by a review of 50 other studies into wind variability and capacity credit (Giebel 2005). This approach however, has been criticised as optimistic and hence, overly generous to wind power (Renewable Energy Foundation 2005). More conservative estimates call for the use of a grid mix average as representative of the avoided emissions factor. However, in a study published by a U.K. think-tank (White, D. & Renewable Energy Foundation 2004), the results of modelling the U.K. grid showed that wind power was more likely to displace "mid merit" generators (i.e. predominately CCGT), while peaking plants such as OCGT, Oil-fired etc would also be required to operate more often, but for short periods. This would seem to justify the approach taken in the current work, where it has been assumed that wind displaces mostly generation at the margin.

This approach can further be justified if the issue is looked at from a financial standpoint. As wind power is free and also has to be given priority under U.K. Government guidelines, it is likely to displace the most expensive conventional generators first. This means that its impact on baseload, which is the cheapest generators on the Grid, is unlikely to be affected for the small levels of penetrations investigated in this work. It is important however to remember that the values estimated here for the emissions factors are only approximations. Short of a detailed full system analysis with real-time operational dispatch modelling, any other method can only approximate the operational situation. This is due to the complexity of interactions that are required to balance supply and demand on the Grid. The emissions intensity (in this case the emissions released into the atmosphere per unit of electricity produced), depends on a variety of factors, including the time of day and year, the price of fuels used for generation, maintenance schedules of power stations, government incentives and barriers to generation and climatic conditions. As such, the emissions intensity of the Grid is an ever-changing value that is hard to establish with historical data, let alone for future conditions.

The operational performance of nuclear and wind power also further complicate the picture. Nuclear power, due to both economic factors (high capital costs require constant operation to guarantee financial payback for investors) and operational inflexibility (nuclear power plants work on a must-run basis, as varying reactor output has a detrimental effect on the operational characteristics of the power plant) is best suited for the generation of "baseload" electricity. This in effect means that it provides the "backbone" generation of the Grid. Wind power, on the other hand, is intermittent by nature, in the sense that although it is possible to determine the power likely to be supplied over the short term, it is not completely possible to guarantee a certain level of supply, especially over the long term. Of course, it has been argued that this problem is in effect no different that the one faced by all operators (where unexpected breakdowns as well as scheduled maintenance breaks occur), and therefore merely requires a restructuring of grid operating procedures. The outcome of this variability is that it is not possible to assume that wind power will displace continuously the same type of power plant (or the same percentages of different power plants making up the mix at any given moment). As a result of the caveats regarding the nature of both wind and nuclear power, it can be argued that short of a system dispatch modeling of the National Grid, any other method will only provide broad approximations to the actual quantities of emissions avoided. It is felt, however, that the method used in this work provides a better assessment of avoided emissions that those used more frequently in the past.

Another product of the estimation of an emissions factor for the two types of energy supply system considered here is the calculation of the total quantity of avoided emissions from the operation of the three power plants. It is important to note, that despite the similarities in the avoided emissions factors for wind and nuclear, the total avoided emissions vary significantly. This of course is a direct result of the different amounts of electricity produced by the power stations over their respective lifetimes. Thus, despite the similar avoided emissions per kWh, the fact that nuclear power has both a longer operational lifetime, a high load factor as well as a greater capacity rating, means that it actually displaces significantly greater quantities of emissions over its lifetime. When the net avoided emissions are calculated (in other words, the avoided emissions minus the emissions from the respective lifecycle), the effect is more pronounced as nuclear has lower lifecycle emissions than wind. Hence it can be argued that even if the two types of powerplant were more balanced, so that they had a similar operational lifetimes and installed capacities, the fact that wind power has load factors less than half those of nuclear power (i.e. 30% as opposed to roughly 70%), nuclear power can potentially displace more emissions.

Using the Carbon Dioxide Gain Ratio further illustrates the above point. By calculating how many times the avoided emissions from displacing other electricity generators exceed the quantity of emissions resulting from the operation of the lifecycle, it can be seen that nuclear power has the highest ratio of the three technologies. As in the case of the energetic indicators however, when the Carbon Dioxide Payback Period is calculated (i.e. the time it takes for a power plant to displace the same quantity of emissions as those generated during its lifecycle operation), the picture is inverted. Since the CDPP is unaffected by the lifetime of operation of the lifecycle, it shows how long it takes the embodied carbon in the capital of lifecycle to be displaced. Thus, because of nuclear power's high up-front and end-of-life liabilities, it performs worse than wind with its comparatively lower embodied emissions.

8.8 Further Implications

The purpose of this section is to highlight other relevant issues both to nuclear as well as wind power, which are not explicitly investigated in this work, but are of fundamental importance to the understanding and comparison of the technologies investigated herein. In all cases however, the exact nature of the issues puts them beyond the scope of this current work and in most cases a fair discussion of the subject would necessitate further studies in their own right.

8.8.1 Energy security

The issue of security of energy supply has come to the prominence both for the U.K. and the European Union as a whole, ever since they become net importers of energy. The vulnerability of both was further illustrated by the effect of gas shortages during the winter of 2006/7 and the dramatic increase in oil prices during the period 2007/2008. As such, both wind power and nuclear power have been hailed as potential solutions to EU's member state's dependence on foreign energy suppliers. However, objections still exist to both forms of energy, using the security of supply as a lynch pin. Indicatively, certain criticisms are presented in the following sections to allow for a balanced view of the issue.

Sharman (Sharman 2005a) argued that wind power in the U.K. should not exceed a given percentage of the Grid's installed capacity, but more importantly that the development of wind power should not be made at the cost of "firm" generating capacity i.e. conventional and nuclear generation. In a previous publication (Sharman 2005b), Sharman had also argued that the sole reason Denmark (a leader in wind energy generation) could maintain such a high level of wind penetration, was because of interconnection with the Nordic Grid. That, being mainly hydro power-based and therefore providing a high capacity dispatchable energy source, allowed Denmark to counterbalance the fluctuations of its wind farms. He thus argued that the U.K., with its few large interconnections to other grids, would not be able to handle large quantities of wind power.

Conversely, a report commissioned by the EU (Lechtenböhmer, Perrels, & et al 2006) created scenarios for the future of the European Union's energy supply, in order to assess its security of supply and ability to meet the challenges of climate change. One of the key findings was that an increase in the use of renewable energy (with offshore wind, biomass and CHP as main drivers) would help in substantially reducing the EU's dependency on imported fossil fuels, while also providing a valuable export commodity. The report did highlight, however, the need for a complete restructuring of the current energy system, but pointed out that this would be a benefit to all players in the field and should not necessarily be seen as a burden of introducing wind power and other renewables into the Grid.

Regarding nuclear power, the report highlighted the issue that despite the fact uranium reserves are expected to last decades, production of uranium would need to be dramatically increased to make up for the increase in demand as well as the shortfall created by the lack of ex-military sources of uranium (currently, the shortfall between mine production and demand is met through the use of uranium from decommissioned nuclear weapons). It thus raised questions about whether there is enough mining capacity to supply projected demand in the future, as well as highlighting the fact that all uranium would have to be imported from outside the EU.

Although there have been many other studies on the effects of energy security of both wind and nuclear, the conclusions reached are broadly similar to those stated above. Thus it can be seen that despite the fact that wind and nuclear power can help diversify the generation mix, nuclear power still creates a dependence on a) an imported fuel and b) on a fuel source that might be in short supply because of production problems and intense international competition. On the other hand, wind power's acknowledged variability means that the technology cannot be called upon in times of higher electricity consumption and therefore its utilisation in the grid past a certain penetration level can also engender risks for security of supply.

8.8.2 Generation Gap

One of the issues facing the U.K. energy sector is the impending so-called "generation gap". In the next 25-20 years, a substantial proportion of the country's electricity generation capacity is expected to be retired, as old nuclear power stations (such as the Magnox and AGR power plants) are shut down and decommissioned and large coal-fired plants become subject to the EU's Large Combustion Plant Directive, which will force most of them to either fit pollution control equipment or close. The size of this shortfall in generation is a subject of some debate but there is a general consensus that the U.K. could face a lack of generation capacity in the short to medium term.

Nuclear and wind power have both been suggested as possible solutions to this impending crises. Many commentators, such as nuclear support and lobbying groups (World Nuclear Association, Uranium Institute and others), have argued that a round of new nuclear build could provide the solution, while also helping to tackle Climate Change. Others have expressed the opinion that, at least, nuclear power should be replaced by new nuclear. A contrasting opinion has been expressed by representatives of renewable energy groups (British and European Wind Energy Associations) as well as environmental groups that have supported the use of renewable energy, and mainly wind power to meet the shortfall.

A key parameter affecting the validity of these claims, however, is when these technologies would be able to contribute to the national generation and by how much. Reports such as those published by Mitchell (Mitchell & Woodman 2006) and Friends of the Earth (Friends of the Earth 2006) have all highlighted the fact that nuclear power has minimal chances of being built in time to contribute in any meaningful way to the shortfalls in generation, especially given the inevitable delays due to planning procedures. Thus, it is generally agreed that nuclear power cannot be supported as a realistic solution to the “generation gap”. The case for renewables, and specifically offshore wind, is considered to be more positive. In general, it is believed that wind power could help to at least mitigate the problems, due to its short construction period which could ensure that capacity is built up quickly. However, in practice, delays due to planning constraints have meant that construction schedules have taken significantly longer than originally planned. Furthermore, the ongoing concerns relating to wind power’s variability and lack of ability to provide dispatchable power mean that it is not ideally suited to replace nuclear and large coal in baseload generation.

The end conclusion of the above considerations is that neither nuclear nor wind power is ideally suited to help address the generation gap in the U.K.’s electricity supply, as neither is likely to built within the timeframes envisaged and to the capacity required. The issue is further complicated by taking into account longer term issues, such as the nature of the electricity supply system that the U.K. should be striving towards, which is further discussed in the following section. Hence, it is argued that althought the “generation gap” has been put forward as deciding factor in the decision between nuclear and wind power, it is maintained in this work that in fact, the issue only serves to confuse matters.

8.8.3 Centralised vs Decentralised Electricity Generation

As mentioned in the previous section, the development of the National Grid can also be seen as a deciding factor in the choice between different energy supply systems.

Currently the National Grid is based on the generation of electricity by large centralised power plants that provide their power to the Grid, which then subsequently transmits it to the load centres. This system has gradually developed over decades and has been the result of the need to generate electricity as efficiently and more importantly, as economically as possible (Patterson 1999). Large power plants such as nuclear power stations are ideally suited to this type of arrangement, as they are inflexible generators (i.e. cannot easily or significantly vary their output to match demand) and therefore are best at providing constant levels of power, also known as baseload power. The focus on purely economically efficient generation however has meant that little attention has been paid to the transmission and end-uses of electricity until recently. Many are now arguing that best way forward is the creation of decentralised grid, based on smaller "embedded" generators that are dispersed around the country and can provide electricity closer to the point of demand. Although there are different levels of decentralisation, renewable energy systems and particularly wind power has been seen as well suited to this type of system. The main argument supporting decentralisation is that through the reduction of generation and transmission losses as well the use of renewables the grid can, in effect, become more sustainable.

The choice therefore, between nuclear and wind power, can have far-reaching consequences for the electricity sector in general. Whereas it is true that the supporting of one or the other technology will not necessarily preclude one form of the Grid or another, it is felt by many that the choice of nuclear power will lead to further "technology lock-in", in other words to the unwillingness to change the centralised generation paradigm, due the massive investment already undertaken to maintain it. The result of this, it has been argued, will be a missed opportunity to move to a more sustainable energy system.

8.8.4 Supply Chain constraints

A further aspect in the comparison of nuclear and wind power is the ability to deliver the energy supply systems on the scale envisaged and required by Government targets. Apart from obvious policy implications, a crucial role in the adoption and integration of each project, is the ability of the U.K. and global supply chain to deliver the technologies within the timescales and financial limits required. Obviously, an energy supply system which performs well but which has few chances of being implemented provides an unbalanced measure of comparison and more generally is of little or no value in meeting the needs of the overall energy system.

A report by IBM (IBM Business Consulting Services 2005) into the U.K. and global supply chain's ability to provide for a new round of nuclear build, presented an overall positive assessment. It made a point of highlighting the fact though, that the U.K. did not have enough indigenous capacities to undertake the project alone and would therefore require significant inputs from the global supply chain. This would mean, given the global competition for materials and expertise that the U.K. would have to make significant improvements to its competitiveness in order to attract the expertise required. Although the Government has taken steps to reduce bureaucratic problems through more streamlined procedures more work is required.

A broadly similar set of proposals were presented to BERR by a study into the condition of the wind turbine supply chain. The report (BERR & Douglas-Westwood Limited 2008), commissioned from consultants Douglas-Westwood Ltd., concluded that given the massive expansion required under Government scenarios, constraints such as skill shortages, as well as component bottlenecks would need to be addressed. In a similar fashion, the report concluded that these constraints also represented opportunities for the domestic market to develop. The main conclusion however, as in the case with the development of nuclear power was that the U.K. needed to make itself more attractive to investment, as well as, developing frameworks to encourage the uptake of practices that could meet the targets set out by the Government.

Further work focusing specifically on the component supply chain, mainly for offshore wind power, was undertaken by the BWEA in (BWEA, BVG Associates, & Westwood 2006). The report looked into all the major issues affecting the deployment of offshore wind farms and concluded that the supply of wind turbines was the single most critical issue, with a special emphasis on gearbox availability) due to the shortage of manufacturers and the worldwide competitions for units. The second most important bottleneck was deemed to be the lack of suitable construction vessels, where a clear incentive was required in order for vessel manufacturers to justify the investments required into bringing more ships online. A final limiting factor in the deployment of wind farms was found to be the grid connection points and the availability of subsea cables and interconnectors. The final problem was more an issue of lead times however, rather than a scarcity of components.

8.8.5 Nuclear Waste and Nuclear Proliferation concerns

A major issue, highlighted almost universally by all reports on nuclear power, is the importance of finding a lasting solution to the issue of nuclear waste. The U.K. Government has started implementing consultation processes to reach a stakeholder agreement on how to manage legacy and new build wastes, following the recommendations of the CoRWM (Committee on Radioactive Waste Management) (CoRWM 2006). However, the process is far from being complete. In this current work, the handling of nuclear waste from a new generation of nuclear power plants, has been assessed based on the information provided by NIREX, as published in their reports on the subject. It has been argued though, that the modelling in that work has not been adequately adjusted for all the parameters relating to new nuclear waste (such as higher burn rates requiring greater shielding for the waste) and therefore probably significantly underestimates the complications associated with this phase. Naturally, these concerns are also carried over into this current work, since the results can only be as good as the data and the assumptions that went into them.

Of equal importance is the need to address the issues of land and material remediation that arise from the radioactive nature of the materials used in the nuclear lifecycle. Nuclear power, as any other power source which is based on solid fuels, has a direct impact on the environment especially in the initial phases of the lifecycle, through mining and processing activities. However, due to the unique nature of the fuel used by the energy supply system, there are also additional issues with respect to the usability and recycling potential of any of the materials used in the lifecycle. These issues need to be addressed carefully, if this technology is to truly attempt to follow the precepts of sustainability.

Hence, it is important to note that there is significant uncertainty about these stages of the nuclear power lifecycle and, as a result, about the overall results. This, however, is not a reflection on the quality of the model developed here as much as it is a true reflection of the problems and unresolved issues associated with this particular technology. As such, any results regarding this energy supply system need to be tempered by these ‘open ended’ concerns, which might have a significant effect on the lifecycle indicators. A conservative conclusion of the assessment of this technology therefore, would be that until real and tangible progress is made to addressing the “Back End” of the fuel cycle, and given the tremendous uncertainties of the implementation of plans, nuclear power should be considered at a disadvantage to renewables, which present a clearer picture, in terms of uncertainties.

Another issue which has not been assessed directly in this analysis of wind and nuclear power is that of the potential dangers arising from the proliferation of nuclear weapons. Ever since the terrorists attacks on the 11th of September 2001 in the United States and the subsequent rise of international terrorism, there has been a heightened concern that nuclear power could provide terrorists with source materials for developing nuclear weapons. It has been argued by several reports (among them the MIT’s (Massachusetts Institute of Technology 2003) as well as (Oxford Research Group 2007) (Krass et al. 1983), (Campaign for nuclear disarmament 2006a)) that nuclear fuel fabrication, and especially fuel reprocessing, could be used to provide materials for nuclear weapons. Naturally, this is not a subject that can be addressed in an engineering evaluation of a technology, but that still does not change the fact that it represents a significant “externality” to the fuel cycle, and therefore can be used as a point of contrast with wind power.

8.9 Closing remarks

Clearly, the effects of the previous issues could be fundamental in the weighting of nuclear and wind power, but cannot be assessed using the current methods of analysis as employed in this work. There is a significant body of work, however, that can help address these issues as well. Hence, the results of this current work should be used in conjunction with the results from studies investigating other impacts of the aforementioned technologies.

It is important to stress that a computational representation can only be as good as the data that is used as an input to it. Thus, while every care has been taken in this research project to ensure that the data sources are as accurate as possible, it is important to remember that the results of the simulations are estimates and should not be taken as absolute values. Especially in the case where the comparative differences between the results are marginal, it is crucial not to overemphasise the importance of these differences, as any conclusion thus supported could easily be altered with a change in the assumptions or the quality of the data used.

8.9.1 A different approach

The focus of this work has been to provide indicators that can be used to compare and contrast nuclear power and wind power in its two prevalent forms, onshore and offshore. Hence, the implicit approach has been that these two energy supply systems should be seen as competitors and, more importantly, as mutually exclusive. This viewpoint has been espoused by certain researchers usually on economic or operational grounds or a mix of both. However, it has been argued by other researchers (e.g. (Hansen & Skinner 2005)), that the choice of technologies should not be seen as an “either or” situation. Nuclear power and wind do not have the same operating characteristics and do not perform the same fuctions for the grid that they are supplying (e.g. nuclear provides baseload generation and, to a very limited extent, some form of grid stability, wind power provides “free” energy therefore reducing fossil fuel dependence etc.). This important aspect tends to be forgotten, if electricity generation is treated as a homogeneous commodity, with methods of electricity production being treated as interchangeable. Each technology should be judged on its merits and for the specific task to which it can be applied. Very few analysts would argue that wind power should be used to replace baseload generation in the current grid configuration; similarly, the idea of using nuclear power to provide load-following services would find few supporters.

Concerns about the lack of political commitment to the undertaking of both courses notwithstanding, it could be argued that both nuclear and wind power have a role to play in meeting the challenges of Climate Change and Sustainability.

9. Conclusions and Recommendations

9.1 Contributions to knowledge

The work herein assessed three technologies, onshore and offshore wind and nuclear power, using the most contemporary data available for a range of parameters, as of the year 2008. These parameters were modeled using information on current and projected data and conditions, in an attempt to model future operating conditions as closely as possible.

A range of impact categories were investigated which are believed to reflect historical current and future concerns about the effectiveness and impacts that energy technologies have on the environment. These categories include parameters such as water and scarce natural materials depletion, which are not yet widely considered in similar analyses.

Finally, the true carbon dioxide displacement potential of the aforementioned technologies was established using transparent methodologies, allowing for adaptation to the specific circumstances, should those change from those used in this work. It is thus hoped that the results of this work can be used to further research in the area, through their incorporation into other projects looking at a broader picture, or directly by policy makers when seeking to assess the relative merits of either technology.

In summary, the research presented in this thesis has accomplished the following:

- Provided a balanced, up-to-date assessment of two major future players (wind and nuclear power) in the U.K. energy industry. As such it has provided much needed clarity to the debate around those technologies.
- Provided results that can be used in other work of broader scope (i.e. lifecycle environmental assessments, techno-economic assessments etc) or can be directly useful to addressing policy questions.
- Created a range of indicators, including for areas seldom commented on in previous assessments of energy technologies.
- Set out a framework for assessing displaced carbon dioxide emissions from the operation of “near zero” carbon dioxide emitting technologies.
- Provided results that contradict and correct many widely held but erroneous positions on both wind and nuclear power.

9.2 Conclusions from current research

Using metrics that were created or adapted for this research, it can be argued that neither energy supply system demonstrates a clear overall advantage. When using the convention of the “energetic opportunity cost” i.e. when wind power is credited for not depleting non-renewable energy sources, the wind farms exhibit higher Energy Gain Ratios than the nuclear power plant. When however the opportunity cost convention is not applied to wind power, the nuclear power plant is seen to have a higher energy ratio than either of the wind farms considered in this analysis. It is noted that both onshore and offshore wind farms pay back their energetic investment faster than the nuclear power plant and this is not adversely affected by the renunciation of the opportunity cost convention (i.e. the wind farms pay back earlier, irrespective of whether the opportunity cost is applied or not).

With respect to the emissions from each of the considered lifecycles, it can be seen that there are not significant differences and that all three technologies can be easily considered as “low carbon” emitters and emitting orders of magnitude less GHG emissions than conventional fossil fuel-fired power plants. In a direct comparison, it can be said that nuclear power produces slightly lower emissions than the onshore wind farm, while the offshore wind farm is the worst of the three “low-carbon” emitters.

An investigation into the land requirements for each technology showed that nuclear power had the best Net-Energy Density of the two technologies, despite the large amounts of land used for supporting activities (‘Front’ and ‘Back End’ uranium processing).It is important to note however, that when the onshore wind farm was only attributed the land-take of the actual installations onsite rather than the whole area required to locate a wind farm, including set-back distances for design purposes, it exhibited an improvement in the normalised land requirements by a factor of 7. However the resulting normalised land requirements were still approximately 8 times higher than those of the nuclear power plant.

The results for the usage of water showed that wind power and specifically offshore wind used large quantities of water per unit electricity produced. Nuclear power fared better, with onshore wind power a close second. The reason for this outcome could be traced back to the large water requirements of steel production and the lower energy output (compared to nuclear) of wind power.

The results for direct construction material requirements did not demonstrate a clear advantage for either technology. For two main construction materials however, steel and concrete, it can be said that nuclear power performed better overall, once again due to its higher output. From the viewpoint of the whole lifecycle, it can be said that there was an even split in the depletion of resources. As such, only the direct weighting of the categories would help distinguish between the values of different materials and therefore show one energy supply system to be more preferable to the other.

With regards to the emissions that could be expected to be avoided through the implementation of these technologies, it can be said as a first instance that avoided emissions factors were estimated to be much lower than those quoted in literature. This can be attributed to the fact that the main displaced generation mix is predominately gas-fired power stations, not coal-fired as has been assumed previously. Both wind and power have very similar displaced emissions factors, i.e. displaced emissions per kWh produced. However, over their lifetime, nuclear power displaces more emissions than wind due to its longer operational lifetime. From the estimation of the Carbon Dioxide Gain ratio, it can be seen that nuclear power displaces a greater percentage of emissions compared to those embodied in its lifecycle. However, both types of wind energy supply systems (onshore and offshore) payback their embodied emissions faster than nuclear power. A final important point is that the assessment of these two technologies needs to be placed in a broader context of the energy grid and society in general, where different weightings to the various impacts may be used. Thus, it is important that the results of the current study are used as a part of a wider interdisciplinary assessment.

9.3 Suggestions for future work

No assessment of complex systems that are intricately connected to their background systems can claim to be definitive or accurate indefinitely. It is also true that any model can only be as good as the data inputs and the assumptions made. As such, there is always scope for further work that could be undertaken using this current research as a starting point. The proposals for future work that are listed below, cover both suggestions with respect to the data inputs, as well as the scope of work to be undertaken.

- As stated previously, it is paramount that the data inputs used in an assessment of the lifecycle of a complex system are as contemporary as possible. This is a necessity because a large proportion of materials and processes involved in the nuclear and wind lifecycles are evolving and can lead to different results, depending on the time that the assessment was undertaken. This is also true of the background processes and inputs, such as the energy mix of the background supply system, as well as the point of origin of the material inputs. Thus it is important to update any such assessment with the newest available data.
- Due to the nature of the lifecycle and the long duration thereof, it is likely that different assessment methods could be investigated. By its nature, the assessments undertaken so far take an end-of-life perspective, in the sense that the modeling reflects the final, aggregated effects of a lifecycle. An inherent flaw in the modeling of any such assessment is the assumption that the background system remains unchanged throughout the lifecycle of the technology being assessed. However, there are always changes over the operational period of the lifecycle, e.g. the electricity mix could become more based on renewables as time progresses. This would then mean that processes in the future i.e. nuclear fuel production and waste management would become less damaging and contribute less to the negative impacts than is now estimated. Thus a “dynamic” time-dependent analysis could provide better final estimates than those calculated using static background systems.
- The current work has been undertaken with a U.K.-centric context in mind, even though by their nature many of the key processes are undertaken in an international environment. Therefore, it is possible that this current work could be made more widely applicable in an international context by investigating the effects of using different inputs to the systems. These variations in inputs could reflect a more international average of values.
- As with the inputs into the assessment itself, the inputs and assumptions used to calculate the avoided emissions would need to be updated accordingly. It is also possible that the methodology could be further refined by using real-time modeling of the National Grid’s processes or baring this, more detailed information over a longer period of time could be sought, thus making the work more reflective of actual power plant operations.

- The current results could be used a part of a wider assessment of the lifecycles in question. This could then lead to an interdisciplinary approach which could encompass other important aspects such as the economics and social implications of the lifecycle. This then would provide a more robust comparison and also highlight other potential issues that this research, by its nature, cannot cover.

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Appendix A

Global Warming Potentials

This section contains the values of assumed Global Warming potentials for the different substances, as calculated in this research.

Substances (airborne)	**IPCC GWP 100a**	
Sulphur, trifluoromethyl pentafluoride	17700	kgCO2eq /kg
Sulfur hexafluoride	22800	kgCO2eq /kg
Propane, perfluoro-	8830	kgCO2eq /kg
Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca	122	kgCO2eq /kg
Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb	595	kgCO2eq /kg
Propane, 1,1,3,3-tetrafluoro-, HFC-245fa	1030	kgCO2eq /kg
Propane, 1,1,2,2,3,3, hexafluoromethoxy- HFE-356pcc3	110	kgCO2eq /kg
Propane, 1,1,1,3,3,3-hexafluoro-, HCFC-236fa	9810	kgCO2eq /kg
Propane, 1,1,1,2,3,3,3-heptafluoro-, HFC-227ea	3220	kgCO2eq /kg
PFPMIE	10300	kgCO2eq /kg
PFC-9-1-18	7500	kgCO2eq /kg
Pentane, perfluoro-	9160	kgCO2eq /kg
Pentane, 2,3-dihydroperfluoro-, HFC-4310mee	1640	kgCO2eq /kg
Nitrogen fluoride	17200	kgCO2eq /kg
Methane, trifluoro-methoxy-, HFE-143a	756	kgCO2eq /kg
Methane, trifluoro-, HFC-23	14800	kgCO2eq /kg
Methane, trifluoro-(difluoromethoxy)-, HFE-125	14900	kgCO2eq /kg
Methane, trichlorofluoro-, CFC-11	4750	kgCO2eq /kg
Methane, tetrafluoro-, CFC-14	7390	kgCO2eq /kg
Methane, tetrachloro-, CFC-10	1400	kgCO2eq /kg
Methane, pentafluoromethoxy-, HFE-134	6320	kgCO2eq /kg
Methane, monochloro-, R-40	13	kgCO2eq /kg
Methane, fossil	25	kgCO2eq /kg
Methane, difluoro-, HFC-32	675	kgCO2eq /kg
Methane, dichlorodifluoro-, CFC-12	10900	kgCO2eq /kg
Methane, dichloro-, HCC-30	8,7	kgCO2eq /kg
Methane, chlorotrifluoro-, CFC-13	14400	kgCO2eq /kg
Methane, chlorodifluoro-, HCFC-22	1810	kgCO2eq /kg
Methane, bromotrifluoro-, Halon 1301	7140	kgCO2eq /kg
Methane, bromochlorodifluoro-, Halon 1211	1890	kgCO2eq /kg
Methane, bromo-, Halon 1001	5	kgCO2eq /kg
Methane, biogenic	25	kgCO2eq /kg
Methane	25	kgCO2eq /kg
HFE-43-10pccc124 (H-Galden1040x)	1870	kgCO2eq /kg
HFE-347pcf2	580	kgCO2eq /kg
HFE-338pcc13 (HG-01)	1500	kgCO2eq /kg
HFE-236ca12 (HG-10)	2800	kgCO2eq /kg
Hexane, perfluoro-	9300	kgCO2eq /kg
Ether, 1,1,2,2-Tetrafluoroethyl methyl-, HFE-254cb2	359	kgCO2eq /kg
Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcf2	575	kgCO2eq /kg
Ethane, pentafluoro-, HFC-125	3500	kgCO2eq /kg
Ethane, hexafluoro-, HFC-116	12200	kgCO2eq /kg

Ethane, chloropentafluoro-, CFC-115	7370	kgCO2eq /kg
Ethane, 2,2,2-trifluoromethoxy-, HFE245fa2	659	kgCO2eq /kg
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	77	kgCO2eq /kg
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	609	kgCO2eq /kg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	10000	kgCO2eq /kg
Ethane, 1,1,2,2-tetrafluoromethoxy-, HFE245cb2	708	kgCO2eq /kg
Ethane, 1,1,2,2-tetrafluoro-, HFC-134	1430	kgCO2eq /kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	6130	kgCO2eq /kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	1430	kgCO2eq /kg
Ethane, 1,1,1-trifluoro-, HFC-143a	4470	kgCO2eq /kg
Ethane, 1,1,1-trichloro-, HCFC-140	146	kgCO2eq /kg
Ethane, 1,1-difluoro-, HFC-152a	124	kgCO2eq /kg
Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	725	kgCO2eq /kg
Ethane, 1-chloro-2,2,2-trifluoro-(difluoromethoxy)-, HCFE-235da2	350	kgCO2eq /kg
Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	2310	kgCO2eq /kg
Dinitrogen monoxide	298	kgCO2eq /kg
Dimethyl ether	1	kgCO2eq /kg
Chloroform	756	kgCO2eq /kg
Carbon dioxide, in air	-1	kgCO2eq /kg
Carbon dioxide, fossil	1	kgCO2eq /kg
Carbon dioxide, biogenic	1	kgCO2eq /kg
Carbon dioxide	1	kgCO2eq /kg
Butane, perfluorocyclo-, PFC-318	10300	kgCO2eq /kg
Butane, perfluoro-	8860	kgCO2eq /kg
Butane, nonafluoromethoxy, HFE-7100	297	kgCO2eq /kg
Butane, nonafluoroethoxy, HFE-569sf2	59	kgCO2eq /kg
Butane, 1,1,1,3,3-pentafluoro-, HFC-365mfc	794	kgCO2eq /kg

Table A.1 GWP factors used in this work based on (Frischknecht and Jungbluth, 2007)

Appendix B

Nuclear Power related calculations

Uranium Mass Fuel Cycle

The electrical output from the nuclear power station is a function of the reactor power rating and the capacity factor. It can be calculated from Equation C.1

$$Eout(kWh) = Power\,Output(MW) \times 1000 \times Capacity\,Factor(\%) \times 365(days) \times 24(hours)$$

The uranium content of the uranium dioxide fuel is a function of the Burn-up and the thermal efficiency of the reactor, can be calculated from Equation C.2:

$$urinUO_2(tons) = {\left({Eout(kWh)} \middle/ {1000000} \right)} \middle/ {\left(Burnup(GWd/tU) \times Thermeff(\%) \times 24(hr) \right)}$$

From the above equation, it is possible to calculate the amount of uranium dioxide required to produce the given electrical output:

$$UO_2(tons) = {urinUO_2(tons)} \Big/ {uUO_2} \qquad \text{(Eq. C.3)}$$

$$\text{where } uUO_2 = \frac{238}{(238 + 2 \times 19)} = 0.881 \qquad \text{(Eq. C.4)}$$

The reactor's Spent Fuel will equal the amount of uranium dioxide in the reactor:

$$Spentfuel = UO_2 \qquad \text{(Eq. C.5)}$$

The solid and liquid wastes from the fuel fabrication phase can be calculated from the following equations:

$$FFsolids(tons) = urinUO_2(tons) \times ffsw(t/tU) \qquad \text{(Eq. C.6)}$$

$$FFliquids(m^3) = urinUO_2(tons) \times fflw(m^3/tU) \qquad \text{(Eq. C.7)}$$

The enrichment stage is the most complex to model. The amount energy used to enrich the uranium (measured in Separative Work Units or SWU) and the level of enrichment of the product and waste (also known as tails) is linked through Equation C.8:

$$SWU = 1000 \times uUF_6 \times \left(UF_6prod(tons) \times f_1 + UF_6tail(tons) \times f_2 + UF_6nat(tons) \times f_3 \right)$$

where:

$$uUF_6 = \frac{238}{(238 + 6 \times 19)} = 0.676 \qquad \text{(Eq. C.9)}$$

$x_1 = Fuelenr(\%)$ the level of fuel enrichment

$x_2 = Enrtailass(\%)$ the level of tails enrichment

$x_3 = na(\%)$ the level of enrichment in natural uranium (0.71%)

$$f_1 = (2x_1 - 1) \times \ln\left({x_1}/{(1 - x_1)} \right) \qquad \text{(Eq. C.10)}$$

$$f_2 = (2x_2 - 1) \times \ln\left({x_2}/{(1 - x_2)} \right) \qquad \text{(Eq. C.11)}$$

$$f_3 = (2x_3 - 1) \times \ln\left({x_3}/{(1 - x_3)} \right) \qquad \text{(Eq. C12)}$$

The amount of uranium hexafluoride produced is related to the required uranium content of the uranium dioxide, as well as the fuel fabrication losses:

$$UF_6\,prod\,(tons) = {urinUO_2\,(tons)}/{\left((1 - fflosses(\%)) \times uUF_6\right)} \qquad \text{(Eq. C.13)}$$

Where the uranium content of the uranium hexafluoride product is given by:

$$uUF_6\,prod(tons) = UF_6\,prod(tons) \times uUF_6 \qquad \text{(Eq. C.14)}$$

The mass of the enrichment tails (also known as depleted uranium) can be estimated from Equation C.15:

$$UF_6tail(tons) = UF_6nat(tons) \times {(Fuelenr(\%) - na(\%))}/{\left(Fuelenr(\%) - Enrtailass(\%)\right)}$$

Where the uranium content is given by:

$$uUF_6tail(tons) = UF_6tail(tons) \times uUF_6 \qquad \text{(Eq. C.16)}$$

The mass of natural uranium hexafluoride, used as an input to the conversion process, can be calculated from Equation C.17, which is dependant on both the required level of enrichment for the final fuel as well as that of the tails from the process:

$$UF_6nat(tons) = {UF_6\,prod\,(tons)}/{\left({(na(\%) - Enrtailass(\%))}/{(Fuelenr(\%) - Enrtailass(\%))} \right)}$$

Where the uranium content of the natural uranium hexafluoride is given by:

$$uUF_6nat(tons) = UF_6nat(tons) \times uUF_6 \qquad \text{(Eq. C.18)}$$

The waste from the conversion stage can be estimated using the following equations, for solid and liquid side-products:

$$Convsolids\ (tons) = uUF_6nat(tons) \times convsolws\ (t\,/\,tU) \quad \text{(Eq. C.19)}$$

$$Convliquids(m^3) = uUF_6nat(tons) \times convliqw\ (m^3\,/\,tU) \quad \text{(Eq. C.20)}$$

The mass of U_3O_8 required from the milling and refining process, is proportional to the natural uranium hexafluoride required for the conversion process and a function of the conversion losses. It should also be noted that as it was assumed that different mines supplied the required ores, an allocation parameter was added to the equation. The subscript “x” is used to denote the mine, from which the ore came from. Equation C.21 gives:

$$m_xU_3O_8\,(tons) = uUF_6nat\,(tons) \times \left(\left(\frac{1}{uU_3O_8} \right) \Big/ \left(1 - convlos(\%)\right) \right) \times alloc_x\,(\%)$$

where $uU_3O_8 = \dfrac{3 \times 238}{(3 \times 238 + 8 \times 16)} = 0.848$ (Eq. C.22)

The mass of the uranium content in the given quantity of U_3O_8 is given by:

$$m_xuinU_3O_8\,(tons) = m_xU_3O_8\,(tons) \times uU_3O_8 \quad \text{(Eq. C.23)}$$

The losses from the milling stage are dependant on the ore grade per U_3O_8 uranium content which is calculated by dividing the ore grade by the quantity of uranium in U_3O_8:

$$og_xU_3O_8\,(\%) = oregrd_x\,(\%) \big/ uU_3O_8 \quad \text{(Eq.C.24)}$$

If the result of the above equation is < 0.1, then the milling losses are given by:

$$milllos_x\,(\%) = \left(10^{1 + \left(\ln(10) + \ln(og_xU_3O_8)\right) \big/ \ln(10) + \ln(0.002)} \right) \quad \text{(Eq. C.25)}$$

else they are calculated by:

$$milllos_x\,(\%) = 1 \big/ og_xU_3O_8 \quad \text{(Eq. C.26)}$$

Finally, the amount of ore required from each mine is evaluated by the following equation:

$$ore_x\,(tons) = \frac{10000}{\left(\dfrac{(oregrd_3 \times (100 - milllos_x))}{\dfrac{1}{uU_3O_8}}\right)} \times m_x U_3O_8 \qquad \text{(Eq. C.27)}$$

while the uranium content of the ore is given by:

$$uinore_x = {}^{100}\!\big/_{(100 - milllos_x)} \times m_x uinU_3O_8 \quad \text{(Eq. C.28)}$$

Wastes from mining can be given by:

$$wrock_x = ore_x \times worerat_x \qquad \text{(Eq. C.29)}$$

All calculations are based on the equations used in (Krass et al. 1983) and (Diehl, 2003).

Mine and Mill Data

Ranger Mine and Mill							
YEAR	**1995**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Product (t U_3O_8)	1,616	4,201	4,241	5,139	5,140	6,000	n/a
Energy Use							
Total (TJ_{th})	299.2	836	721	848	931	1,140	n/a
Per Unit							
GJ_{th}/ t U_3O_8	185.1[•]	199	170	165	181.1	190	n/a
GJ_{th}/t Ore	0.52	0.49	0.42	0.41	0.45	0.47	n/a
Diesel for electricity (l/MWh)	n/a	n/a	n/a	265	n/a	n/a	278.5
Other							
Freshwater (l)	n/a	191,000,000	227,000,000	149,000,000	n/a	n/a	n/a
(l / t U_3O_8)	n/a	45,000	53,000	29,000	n/a	n/a	40,310

Table B.1 Data for operation of Ranger mine

[•] From (Solberg-Johansen), requirements are 0.018MWh/kgU_3O_8, which in this work is assumed to be generated by a diesel-electric generator with an efficiency of 35%

Olympic Dam Mine & Mill					**Uranium Oxide specific**
YEAR	**2000**	**2001**	**2002**	**2003**	**2004**	**2004**
Ore (t)	8,914,000	9,339,000	8,875,000	8,387,000	8,887,000	**8,887,000**
Product (t U3O8)	-	-	-	-	4403	**4403**
Energy Use						
Total (TJ_{th})	5,183	5,216	4,881	4,667	5,477	**1369**
Electricity	-	-	-	-	3,066	**767**
Diesel	-	-	-	-	839	**210**
LPG	-	-	-	-	846	**212**
Coke	-	-	-	-	300	**75**
Other fuels	-	-	-	-	426	**107**
Per Unit						
GJ_{th}/ t U_3O_3	-	-	-	-	-	**311**
GJ_{th}/ t Ore	0.56	0.59	0.62	0.68	0.58	**-**
Other						
Explosives (t)	-	-	-	-	3,995	**999**
Ammonia (t)	-	-	-	-	2,666	**667**
Sodium Hydroxide (t)	-	-	-	-	3,420	**855**
Cement (t)	-	-	-	-	89,316	**22,329**
Fly ash (t)	-	-	-	-	161,787	**40,447**
Quicklime (t)	-	-	-	-	11,008	**2,752**
Sodium Cyanide (t)	-	-	-	-	105	**26**
Sulphur (t)	-	-	-	-	58,405	**14,601**
Sulphuric acid (t)	-	-	-	-	22,366	**5,592**
Sulphur Dioxide (t)	-	-	-	-	327,160	**81,790**
Freshwater (litres)	10.56 x10^9	10.35 x10^9	10.73 x10^9	10.47 x10^9	11.9 x10^9	**2.98 x10^9**
(litres / t U_3O_3)	-	-	-	-	-	**675,789**
Land use (km^2)	13.16	13.16	13.5	13.86	14.08	**3.52**
Landfill waste (t)	-	-	-	-	7,730,000	**1,932,500**

Table B.2 Data for operation of Olympic Dam mine

Rössing Mine and Mill								
YEAR	**1995(1)**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005 (2)**
Ore (t)	6,759,662	10,463,000	11,039,000	9,084,000	8,769,000	8,347,000	10,972,000	-
Product (tU_3O_8)	2,366	3,171	3,201	2,643	2,751	2,401	3,582	3,711
Energy Use								
Total Energy– TJ_{th}	1,273	1,248	1,133	979	999	915	1,096	1,550*
Per Unit								
GJ_{th}/t U_3O_8	537.9	393.6	354.0	370.4	363.1	381.1	306.0	418
GJ_{th}/t Ore	0.19	0.12	0.10	0.11	0.114	0.11	0.10	-
Other								
Fresh water consumption – m^3	-	2,779,000	2,312,000	2,053,000	2,175,000	2,486,000	3,003,000	3,200,000
Fresh water per t uranium oxide – m^3/t U_3O_8	-	876.4	722.3	776.8	790.6	1035.4	838.4	862.3
Ratio of fresh water : total water	-	0.27	0.22	0.22	0.25	0.35	0.33	-
Seepage water collected – $000m^3$	-	2,102	2,709	1,609	2,001	1,963	2,381	-
Waste rock removed – tonnes	-	15,607,000	9,787,000	12,033,000	13,015,000	10,434,000	8,139,000	-
Ratio ore processed: waste rock removed	-	0.67	1.13	0.75	0.67	0.8	1.35	-

Table B.3 Data for operation of Rossing mine, based on company's environmental reports with data from (1) (Solberg-Johansen) and (2) (IJG Securities (Pty) Ltd and Smith)

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* In (IJG Securities (Pty) Ltd and Smith) it is stated that Rössing used 187,331MWh of electricity in 2005, while (Solberg-Johansen), states, in 1995, the mine had an electricity requirement of 0.065MWh / kgU_3O_8. In both cases, the values have been translated back to primary energy requirements using a grid generation efficiency of 43.5%

Nuclear Power Plant Construction

	IAEA (taken from (Storm van Leeuwen 2004))	**ORNL** (Bryan and Dudley, 1974)	**R&K** (taken from (Storm van Leeuwen 2004))	**Shaw** (taken from (Storm van Leeuwen 2004))	**LAKO** (taken from (Storm van Leeuwen 2004))	**ORNL** (ORNL, Resources for the Future, and DoE 2005)	**NP2010** (DoE 2005)
	1971	***1974***	***1974***	***1977***	***1984***	***1995***	***2005***
Tonnes per GW							
Sum metals	37,311	36,986	12,809	26,760	66,400	34,965	71,000
Reinforcement steel	33,000	-	-	17,690	40,000	22,140	46,000
Structural Steel	-	-	-	9,070	-	9,533	25,000
other steel	-	-	10,000	-	25,000	2,009	-
carbon steel	-	32,731	-	-	-	-	-
iron	-	-	-	-	-	737	-
stainless steel	2,100	2,080	-	-	-	-	-
galvanized iron	1,300	1,257	-	-	-	-	-
copper/copper alloy	740	694	2,000	-	1,200	-	-
brass + bronze	-	35	-	-	-	-	-
aluminium	20	18	45	-	200	-	-
chromium	-	-	150	-	-	-	-
‘inconel’	100	124	-	-	-	-	-
lead	50	46	8	-	-	-	-
nickel	1	1	100	-	-	-	-
manganese	-	-	400	-	-	-	-
zinc	-	-	100	-	-	-	-
other metals	-	-	6	-	-	546	-
insulation	-	922	-	-	-	-	-

asbestos	-	-	45	-	-	-	-
magnesia	-	-	-	-	-	-	-
paint	-	19,250 (1)	-	-	-	-	-
wood	-	5,600 (2)	-	-	-	-	-
concrete (m^3) (3)	180,000	180,000	-	256,800	450,000	570,893	844000
(tonnes) (3)	75,000	75,000	-	107,000	187,500	237,872	351,667
piping (m)	-	-	-	91,000	-	-	-
cables&conduct. (m)	-	-	-	1,130,000	-	-	-
framework (m^3)	-	-	-	53,800	-	-	-
large bore pipe (km)	-	-	-	-	-	-	79
small bore pipe(km)	-	-	-	-	-	-	131
cable tray(km)	-	-	-	-	-	-	67
Conduit (km)	-	-	-	-	-	-	366
power cable (km)	-	-	-	-	-	-	427
control wire (km)	-	-	-	-	-	-	1,646
Instr. tubing (km)	-	-	-	-	-	-	226
Total mass	217,311	242,758	12,854	283,560	516,400	605,858	915,000
Ratio Concrete/R. steel	5.5	-	-	14.5	11.3	25.8	18.3
Ratio Reinf. Steel/Struct. Steel	-	-	-	1.95	-	2.32	1.84
Ratio Concrete/ Total Steel	**4.8**	**4.9**	**-**	**9.6**	**6.8**	**16.3**	**11.9**

Table B.4 Summary of NPP construction material from various studies

(1) 17500 m^3 assuming 1.1 t/ m^3

(2) 4.8x10^6 bd ft - 11330m^3 - 5600t assuming 0.5 t/ m^3

(3) based on a density of 2.4 t/ m^3

Comparison of material requirements from the 1971 and 2005 studies

As stated above, the “bill of materials” used in this research are taken from the 2005 study. However, in the interests of comparison, it was decided to also try and adapt the older (and also more complete) set of data that was based on an actual “bill of materials” for 1970’s reactor deisgn, as published by the Oak Ridge National Laboratory in 1974 (Bryan and Dudley, 1974). The information in the aforementioned report was modified according to the specifications of the Toshiba/Westinghouse AP1000 reactor model, as provided in (British Nuclear and Westinghouse Electric Company LLC, 2002), (Energetics Incorporated, 2005) and (Schulz, 2006). In the original 1974 report, the required materials for the construction of a NPP, were divided into groups, depending on the building they constituted a part of (e.g. reactor building, steam generator building etc). As no exact data concerning the material requirements and breakdown of the AP1000 were readily available, assumptions had to be made based on the available published information. These assumptions are, hence, based on the published information relating to the improvements and reductions in materials and parts, compared to a conventional nuclear power plant of similar output (approx. $1GW_e$), as detailed in the above reports. It should be noted that decisions to as to where to apply the reductions have been mostly arbitrary and are therefore no more than educated guesses. They are included merely as a contrast to the second set of data from the NP2010 report (that is based on more up to date estimates).

ORNL 1974 study

Material/volume reductions compared to conventional designs

As mentioned in the introduction, the reductions in material quantities are based on the information published by the manufacturers in various reports (Schulz 1547-57;Vande and NIREX UK LTD;British Nuclear and Westinghouse Electric Company LLC). Specifically, the following data was provided in those reports:

1. 50% fewer valves
2. 35% fewer pumps
3. 80% less piping
4. 80% less HVAC systems
5. 45% less “seismic-build” volume
6. 70% less cable

Based on the above values, assumptions concerning the applicability of each reduction to the different building components were made based. These assumptions are highlighted in each section below.

Nuclear Power Plant Facilities

Structures and Site Facilities

The Structures and Site Facilities segment covers such areas as:

- General Site Improvements (roads, fences drainage etc), waterfront improvements (e.g. breakwaters), highway access, railway access and waterway access
- Reactor Building
- Turbine Building
- Reactor Auxiliaries
- Fuel Storage
- Miscellaneous Buildings

The assumption was made that 45% reduction in seismic building volume was more applicable to this unit of the modelling. As such, a reduction of 22.5% each was applied to the listed quantities of carbon steels and concrete respectively.

Reactor plant Equipment

- Reactor plant
- Main heat transfer system
- Cooling system
- Radioactive waste system
- Instrumentation
- Fuel handling system

A reduction of 50% in valves was arbitrarily associated with this modelling unit, and was represented as 25% reduction in stainless steels with an equal reduction of carbon steels. The reduction in pumps of 35% was also applied to this unit, resulting in an equal reduction of 18% in iron and stainless steel quantities.

Turbine Plant Equipment

- Turbine-Generators
- Heat Rejection System
- Condensing Systems
- Feed-heating systems
- Instrumentation

The Turbine plant was chosen as the most relevant for the 80% reduction in piping, based on the bill of materials provided with the original data. This was translated as an equivalent reduction of stainless steel requirements for this unit.

Electric Plant Equipment

- Switchgear
- Station Service equipment
- Switchboards
- Protective Equipment
- Power and Control equipment

A 70% reduction in cabling was represented in the model as a reduction in the copper quantities listed in this unit. Other relevant material quantity reductions (e.g. wire plastic cladding) were omitted as they were assumed to be negligible in comparison.

Miscellaneous Equipment

- Transportation and lifting equipment
- Air and water service systems
- Communication Equipment

The reduction of HVAC equipment by 80% was translated mainly as an equal reduction in carbon and stainless steels.

DoE NP2010 study

The most recent data comes from the DoE NP2010 project, as detailed in (DoE). The report includes a breakdown of materials that will be required to build a single GEN III+ unit. The list of materials contains detailed information about the amount of steel and concrete required for construction, but also contains lots of other data that is not in a form suitable for modelling. Such examples include giving information on pipes, cables and wires in ‘km’, with no other supporting information as to material type. The exact data used in the model were shown in Table B.4.

Results from comparison of construction material quantities

A comparison between the reduced mass values based on the 1971 reactor data and the information concerning the GEN III+ reactor, indicates that there is very few difirences between the 2 datasets, despite the age and reduction assumptions of the first and the incomplete and fragmented nature of the second. An important point to note is that the total mass of the GEN III+ is about 4 times higher than the 1971 design. The quantities of steel used in the design have doubled and those of concrete have quadrupled. It should be noted, that it is generally accepted that both concrete and steel have among the highest embodies energy and carbon values. Thus it was felt, that despite the more recent data set being incomplete (in comparison to the 1971 study), the materials with the highest impact were sufficiently covered to allow the omission of the other data.

Appendix C

Wind Power related calculations

Wind Data Analysis

From the NOABL database, the wind speeds at different heights for the Whitelee wind farm are shown below:

for the 1km grid square 258 645 (NS5845)

Wind speed at 45m agl (in m/s)

9.1	**9.2**	**9.4**
8.9	**9**	**9.2**
8.5	**8.5**	**8.4**

Wind speed at 25m agl (in m/s)

8.6	**8.8**	**8.9**
8.3	**8.5**	**8.7**
7.9	**7.8**	**7.7**

Wind speed at 10m agl (in m/s)

7.9	**8.2**	**8.4**
7.6	**7.7**	**8**
7.2	**7.1**	**6.9**

The same database estimated the following values for the location of the Salsburgh meteorological station:

for the 1km grid square 282 664 (NS8264)

Wind speed at 45m agl (in m/s)

8.2	**8.6**	**8.6**
8.3	**8.7**	**8.9**
8.1	**8.4**	**8.8**

Wind speed at 25m agl (in m/s)

7.6	8	8
7.6	8.1	8.4
7.4	7.8	8.2

Wind speed at 10m agl (in m/s)

6.7	7.3	7.3
6.8	7.4	7.8
6.6	7	7.5

An image of the Whitelee site, with a scale of 1:50,000 can be seen below:

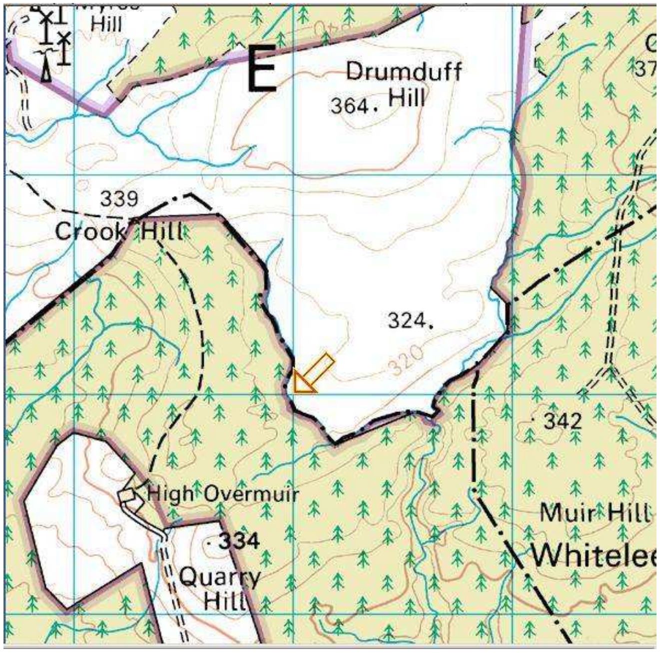

Figure C.1 1:50k scale map of the Whitelee site (taken from Streetmap, 2008)

Mass scaling equations

For the generation of the material quantities for the 3.6MW and 5MW wind turbines, information and scaling equations were taken from (Fingersh et al. 2006). The report contained information about the how various components could be scaled based on semi-empirical formulas. The equations used in this current research are outline below as well as an indication as to where they were employed:

Blades

The equations for calculating blade mass are given below:

$$\text{Baseline: mass} = 0.1452 * R^{2.9158} \text{ per blade (1)}$$
$$\text{Advanced: mass} = 0.4948 * R^{2.53} \text{ per blade (2)}$$

where R is the rotor radius. The advance case refers to products developed by a wind turbine blade, LM Glasfiber, that “take advantage of a lower-weight root design”. In this work, Equation (1) was used for the calculation of the blade mass for the 3.6MW turbine, while for the 5MW turbine the advanced formula was used, for the reasons described in Chapter 6.

Hub

The Hub mass is given by:

$$\text{Hub mass} = 0.954 * (\text{single Blade mass}) + 5680.3$$

Pitch Mechanisms and Bearings

The bearing mawas calculated as a function of the blade mass for all three blades. Actuators and drives were estimated as 32.8% of the bearing mass + 555 kg.

$$\text{Total Pitch Bearing Mass} = 0.1295 * (\text{Total Blade mass (3 blades)}) + 491.31$$
$$\text{Total Pitch System Mass} = (\text{Total Pitch Bearing Mass} * 1.328) + 555$$

Nose Cone

Nose cone mass = 18.5 * rotor diameter – 520.5

Low-speed Shaft

$$\text{Low-speed Shaft mass} = 0.0142 * \text{rotor diameter}^{2.888}$$

Main Bearings

$$\text{Main bearings mass} = (\text{rotor diameter} * 8/600 - 0.033) * 0.0092 * \text{rotor diameter}^{2.5}$$

Gearbox

In the NREL study (Fingersh et al. 2006), four designs were covered and include a three-stage planetary/helical gearbox with high-speed generator, single-stage drive with medium-speed generator, a multi-path drive with multiple generators, and a direct drive with no gearbox (see note).

Three-stage Planetary/Helical

$$\text{Mass} = 70.94 * \text{low-speed shaft torque}^{0.759}$$

Single-stage drive with medium-speed generator

$$\text{Mass} = 88.29 * \text{low-speed shaft torque}^{0.774}$$

Multi-path drive with multiple generators

$$\text{Mass} = 139.69 * \text{low-speed shaft torque}^{0.774}$$

N.B. The direct drive does not have a gearbox

Mechanical Brake, High speed Coupling and associated components

Brake cost is calculated as a function of machine rating. This function was developed from the WindPACT rotor study cost data, converted to a function based on machine rating. The mass is then calculated based on an assumption of $10/kg.

$$\text{Brake/coupling cost} = 1.9894 * \text{machine rating} - 0.1141$$

$$\text{Brake/coupling mass} = (\text{brake/coupling cost}) / 10$$

Generator

Although there are is a large variety of gearboxes available commercially, the NREL study limited there work to high-speed wound rotor designs used with high-speed gearboxes, and permanent-magnet generators used with single-stage gearboxes, multi-generator gearboxes, and direct drive.

Three stage drive with high-speed generator

$$\text{Mass} = 6.47 * \text{machine rating}^{0.9223}$$

Single Stage drive with medium speed permanent magnet generator

$$\text{Mass} = 10.51 * \text{machine rating}^{0.9223}$$

Multi-path drive with permanent magnet generator

$$\text{Mass} = 5.34 * * \text{machine rating}^{0.9223}$$

Direct Drive

$$\text{Mass} = 661.25 * \text{low speed shaft torque}^{0.606}$$

Yaw-drive and bearing

$$\text{Total yaw system mass} = 1.6 * (0.0009 * \text{rotor diameter}^{3.314})$$

Mainframe

The mainframe cost is calculated as a function of rotor diameter. The mainframe mass also depends on the type of drive train installed as each drive train design distributes its load in a different manner and will have a different length.

Three-Stage Drive with High-Speed Generator

$$\text{Mainframe mass} = 2.233 * \text{rotor diameter}^{1.953}$$

Single-Stage Drive with Medium-Speed, Permanent-Magnet Generator

$$\text{Mainframe mass} = 1.295 * \text{rotor diameter}^{1.953}$$

Multi-Path Drive with Permanent-Magnet Generator

$$\text{Mainframe mass} = 1.721 * \text{rotor diameter}^{1.953}$$

Direct Drive

$$\text{Mainframe mass} = 1.228 * \text{rotor diameter}^{1.953}$$

Platforms and Railings

$$\text{Platform and railing mass} = 0.125 * \text{mainframe mass}$$

Hydraulic and Cooling Systems

$$\text{Hydraulic, cooling system mass} = 0.08 * \text{machine rating}$$

Nacelle Cover

The NREL study derived a single function for all drive train configurations, as data were too scarce to develop individual formulas for different drive train configurations. The calculations are a function of machine rating in kW. Nacelle cover mass was derived from Nacelle cover cost.

Nacelle cost = 11.537 * machine rating + 3849.7
Nacelle mass = nacelle cost / 10

Tower

All towers discussed here are steel tubular towers. The tower mass is scaled with the product of the swept area and hub height. Given any turbine diameter, hub height, and tower mass, a comparison can be made between steel tubular towers. The mass of the tower can be calculated from:

Baseline: mass = 0.3973 * swept area * hub height – 1414
Advanced: mass = 0.2694 * swept area * hub height + 1779

The baseline case is based on standard technology for 2002, while the advanced case assumes advanced technologies including tower feedback in the control system, flap-twist coupling in the blade, and reduced blade solidity in conjunction with higher tip speeds.

The NREL makes a point of highlighting that much of the data used to develop scaling functions for machines of greater than 1 to 2 MW is based on conceptual designs. Many components are scaled using functions that are close to a cubic relationship. This is what would normally be expected for technologies that did not undergo design innovations as they grew in size. In reality, this is not what would be expected for future designs as innovation is expected to help reduce many of the material requirements. This means that the equations used in this work represent very much a conservative estimate, in line with the methodology of this work.

Wind Turbine material breakdown

Enercon E-66 wind turbine (1500kW)

The material requirements were taken directly from (Chataignere and Le Boulch). From this data, it was possible to estimate the ratio of each material to the total mass of the component. These ratios were then used as scaling factors for the larger wind turbines (3.6 and 5MW).

	Material	**Mass**	**Unit**	**Total**	**Mass ratio**[*]
Blade (1)	Aluminium	33	kg	5384	0.006
	Fibre Glass	2188	kg		0.406
	Epoxy resin	1516	kg		0.282
	Hardener	525	kg		0.098
	Polyamide	76	kg		0.014
	Polyethene	228	kg		0.042
	PVC foam	279	kg		0.052
	PVC	131	kg		0.024
	Paint	184	kg		0.034
	Rubber	55	kg		0.010

---

[*] Ratio of material mass to overall component weight

	Others	169	kg		0.031
Tower	Steel	144182	kg	153094	0.942
	Galvanised steel	4695	kg		0.031
	Paint	4217	kg		0.028
Generator	Copper	8988	kg	40690	0.221
	Steel sheet	17927	kg		0.441
	Steel (no alloy)	13258	kg		0.326
	Steel (galvanised, low grade)	105	kg		0.003
	Steel (alloy, high grade)	14	kg		0.000
	Paint	150	kg		0.004
	Others	248	kg		0.006
Rest of nacelle	Steel (no alloy)	10780	kg	51591	0.209
	Steel (alloy, low grade)	9101	kg		0.176
	Steel (galvanised, low grade)	1224	kg		0.024
	Cast steel	3708	kg		0.072
	Cast iron	21027	kg		0.408
	Aluminium	127	kg		0.002
	Copper	293	kg		0.006
	Fibre glass	924	kg		0.018
	Unsaturated polyester resin	2159	kg		0.042
	Electronics	120	kg		0.002
	Paint	504	kg		0.010
	Others	1624	kg		0.031
Grid Connection	Steel sheet	1300	kg	27734	0.047
	Steel (alloy, low grade)	927	kg		0.033
	Steel (alloy, high grade)	630	kg		0.023
	Steel (galvanised)	715	kg		0.026
	Steel (for construction)	741	kg		0.027
	Iron	1042	kg		0.038
	Copper	6119	kg		0.221
	PVC	747	kg		0.027
	Gear oil	940	kg		0.034
	Rest of electrics	1065	kg		0.038
	Electronics	1283	kg		0.046
	Light weight concrete	12000	kg		0.433
	Others	225	kg		0.008
Deep foundations	Normal concrete	575000	kg	614709	-
	Steel (construction)	26300	kg		-
	Steel (no alloy)	13243	kg		-
	PVC	166	kg		-

Table C.1 Material inputs to the Enercon E-66 wind turbine

3.6MW model wind turbine

For the 3.6MW turbine, it was assumed that it used a three-stage planetary/helical gearbox, as stated in (Lewis Wind Power Limited and AMEC). The mass of the generator supposedly used in the 3.6 MW was not available from the manufacturer's brochures. As such it was decided to use the most conservative estimate for the mass of the unit, and based on the equations above, it was assumed that a system utilising a

Single Stage drive with medium speed permanent magnet generator was used. Having used this assumption, the mainframe was also scaled accordingly. Finally, the tower was modelled using the baseline equation, providing a conservative estimate.

Using the above equations and comparing the total weights of the components to the published figures for the Siemens 3.6MW (Lewis Wind Power Limited and AMEC), it can be seen that the NREL equations underestimate the masses:

Masses		Siemens figures	NREL estimates	Difference in estimates
Rotor	tonnes	95	74	-22%
Nacelle	tonnes	125	108	-13%
80m tower	tonnes	250	285	14%

Table C.2 Comparison of masses for the Siemens and NREL turbine models

The published masses were not use to scale the wind turbine, because it would have not been possible to calculate the split of materials between components (i.e how much should be attributed to the generator, nacelle etc), due to the aggregated nature of the value.

A further addition to this wind turbine was the inclusion of the different types of offshore foundations. The original information was also provided by (Chataignere and Le Boulch), with data calculated for a generic 2.5MW turbine. This information was then scaled up, based on wind turbine installed capacity (MW rating). This method was chosen, as not other scaling equations were available from literature, while the ECLIPSE study also uses similar methodologies. A departure from the given data was the addition of other materials to the list for the foundations (namely concrete). This change was made after the consultation of the London Array Environmental Statement (RPS and London Array Ltd), where the following estimates were given:

Foundation type	**London Array Environmental Statement**	
Monopile	Steel	300000-700000 kg
	Concrete	25000-100000 kg
	Stones for scour	150-1000 m^3
Caisson	Concrete	2000000-5000000 kg
	Steel	200000-400000 kg
	Rock (sand)	2000-4000 m^3
	Stones for scour	2000 m^3
Tripod	Steel	900000-1200000 kg
	Concrete	25000-100000 kg

Table C.3 Material estimations for the London Array

Using the above estimates, it was decided to scale the concrete requirements using the ratio of the steels (i.e the steel requirements from the London Array and those of the ECLIPSE study) as a scaling ratio. In both the case of the monopile and the tripod foundations, the concrete was scaled based on the higher range of steel values from the Environmental Statement. An important fact to note is that, whereas for the monopile and the caisson foundation types, the steel requirements from the two studies are broadly in agreement, for the tripod foundations there is a significant deviation in the estimates. Specifically, the London Array Environmental Statement has an upper estimate of 1,200 tonnes of steel, whereas by using the scaling rules and the ECLIPSE values, the total amount of steel was calculated to be only 189 tonnes. This factor of 10 difference in the masses, can possibly be attributed to the fact that the tripod foundation type represent a theoretical scenario, as none have ever been used for wind turbine foundations. As such, there is no actual data to inform estimates.

Due to the lack of any further information in the London Array Environmental Statement however, it was decided to use the ECLIPSE estimate, even though they might provide an understatement of the steel quantity requirements.

A further point of interest is the estimates for the offshore and onshore grid connections. The values for the onshore connection in the ECLIPSE reports are based on the scaling of the equivalent entry for the 1500kW turbine, while the offshore grid connections are based on the authors estimations. However, it was felt that the offshore grid connection module provided in ECLIPSE, underestimated the quantities required, since they were significantly lower than those for the onshore grid connection. It is position of this author, that the offshore connection has additional material requirements, as there is a need for offshore substations as well as the laying of power cables to shore, in addition to the need for an onshore substation. As a result, the decision was made include the both offshore and onshore modules in this work, with the change that the onshore grid connection materials were reduced by the amount specified for the offshore grid connection. This most probably results in an overestimation of the material requirements for the wind farm, but provides a conservative estimate.

	Material	**Mass**	**Unit**	**Total**
Blade (1)	Aluminium	90	kg	14638
	Fibre Glass	5949	kg	
	Epoxy resin	4122	kg	
	Hardener	1427	kg	
	Polyamide	207	kg	
	Polyethene	620	kg	
	PVC foam	759	kg	
	PVC	356	kg	
	Paint	500	Kg	
	Rubber	150	Kg	
	Others	459	Kg	
Tower				284642
	Steel	268072	kg	
	Galvanised steel	8729	kg	
	paint	7841	kg	
Generator				20025
	Copper	4423	kg	
	Steel sheet	8823	kg	
	Steel (no alloy)	6525	kg	
	Steel (galvanised, low grade)	52	kg	
	Steel (alloy, high grade)	7	kg	
	Paint	74	kg	
	Others	122	kg	

Rest of nacelle				88470
	Steel (no alloy)	18486	kg	
	Steel (alloy, low grade)	15607	kg	
	steel (galvanised, low grade)	2099	Kg	
	cast steel	6359	Kg	
	cast iron	36058	Kg	
	aluminium	218	Kg	
	copper	502	Kg	
	fibre glass	1585	Kg	
	unsaturated polyester resin	3702	Kg	
	electronics	206	Kg	
	Paint	864	Kg	
	others	2785	Kg	
	gear oil	600	Kg	
3600 kW, offshore, 1 WT, 25km, grid connection				10972
	steel	6336	kg	
	copper	4634.496	kg	
	SF_6	1.08	kg	
3600 kW offshore, monopile foundations				682685
	steel (hot rolled coil, BF route)	14193	kg	
	steel (galvanised)	574560	kg	
	concrete	85336	kg	
	steel (highly allied)	8597	kg	
3600 kW offshore, caisson foundations				2.07E+07
	normal concrete	3888000	kg	
	steel (construction)	288000	kg	
	steel (hot rolled coil, BF route)	9612	kg	
	gravels	16272000	kg	
	steel (galvanised)	195840	kg	
	steel (highly allied)	3210	kg	
3600 kW offshore, tripod foundations	Materials/fuels			193770
	steel (hot rolled coil, BF route)	14162	kg	
	steel (galvanised)	172800	kg	
	steel (highly allied)	1571	kg	
	concrete	5237	kg	
Grid Connection (onshore substation)	Steel	4015	kg	55591
	iron	2501	kg	
	copper	10051	kg	
	PVC	1793	kg	
	Gear oil	2256	kg	
	Rest of electrics	2556	kg	
	electronics	3079	kg	
	Light weight concrete	28800	kg	
	others	540	kg	

Table C.4 Material inputs to the 3.6MW wind turbine

5MW wind turbine model

The modelling of the 5MW turbine was based on a combination of data. The blades were modelled based on the NREL's "advanced" case using the LM Glasfiber case study (Equation 2). This equation was chosen, as it stated in the REpower 5M brochure {REpower Systems AS, 2007 536 /id}, that they helped with the design of the wind turbine. The rest of the wind turbine, with the exception of the tower component, is scaled up using a power ratings ratio, utilising the ECLIPSE 4.5MW turbine as a basis. For the tower, it was necessary to use the NREL scaling equations, as the baseline 4.5 MW turbine was modelled using a concrete tower. However, for offshore, it was felt that a concrete tower would reflect current practices, so the equation for the "baseline" tower unit was used. This was chosen over the "advanced" case equation since this would provide a conservative estimate. For the onshore and offshore grid connections, the same procedure was used as for the 3.6MW turbine.

	Material	Mass	Unit	Total
5000 kW blade (1) based on 4500kW				16607
	Aluminium	102	kg	
	Fibre Glass	6749	kg	
	Epoxy resin	4676	kg	
	Hardener	1619	kg	
	Polyamide	234	kg	
	Polyethene	703	kg	
	PVC foam	861	kg	
	PVC	404	kg	
	Paint	568	kg	
	Rubber	170	kg	
	Others	521	Kg	
Tower				394901
	steel	371912	kg	
	galvanised steel	12111	kg	
	paint	10878	kg	
5000 kW nacelle based on 4500kW				393915
	Steel (no alloy)	127349	kg	
	Steel (alloy, low grade)	48216	kg	
	Steel (alloy, high grade)	74	kg	
	steel (galvanised, low grade)	7041	kg	
	cast steel	19644	kg	
	cast iron	111397	kg	
	aluminium	673	kg	
	copper	49169	kg	
	fibre glass	4895	kg	
	unsaturated polyester resin	11438	kg	
	electronics	636	kg	
	Paint	3465	kg	
	others	9918	kg	
	gear oil	1200	kg	
5000 kW, offshore, 1 WT, 25km, grid connection				15238.3
	steel	8800	kg	
	copper	6436.8	kg	
	SF6	1.5	kg	

5000 kW offshore, monopile foundations				948174
	concrete	118522	kg	
	steel (hot rolled coil, BF route)	19712	kg	
	steel (galvanised)	798000	kg	
	steel (highly allied)	11940	kg	
5000 kW offshore, caisson foundations				2.87E+07
	normal concrete	5400000	kg	
	steel (construction)	400000	kg	
	steel (hot rolled coil, BF route)	13350	Kg	
	gravels	22600000	Kg	
	steel (galvanised)	272000	Kg	
	steel (highly allied)	4458	Kg	
5000 kW offshore, tripod foundations				269126
	steel (hot rolled coil, BF route)	19670	kg	
	steel (galvanised)	240000	kg	
	steel (highly allied)	2182	kg	
	concrete	7274	kg	
Grid Connection (onshore substation)	Steel	5577	kg	77210
	Iron	3473	kg	
	copper	13960	kg	
	PVC	2490	kg	
	Gear oil	3133	kg	
	Rest of electrics	3550	kg	
	electronics	4277	kg	
	Light weight concrete	40000	kg	
	Others	750	kg	

Table C.5 Material inputs to the 5MW wind turbine

Appendix D

Calculation of avoided emissions

Calculating the BM

Table below adapted from Table 5.11 of Dukes 2007 (DTI 2007)

Power Stations in the United Kingdom

(operational at the end of May 2007)

Company Name	Station Name	Fuel	Installed Capacity (MW)	Year of commission or year generation began	Location
Centrica	Barrow Offshore Windfarm	wind (offshore)	90	2006	North West
E.On UK	Scroby Sands	wind (offshore)	60	2005	East
Vattenfall Wind Power	Kentish Flats	wind (offshore)	90	2005	South East
Beaufort Wind Ltd	North Hoyle	wind (offshore)	60	2003	Wales
Blyth Offshore Wind Ltd	Blyth Offshore	wind (offshore)	4	2000	North East
Beaufort Wind Ltd	Causeymire	wind	48	2004	Scotland
Beaufort Wind Ltd	Bears Down	wind	10	2001	South West
Llangwyryfon Windfarm Ltd	Llangwyryfon	wind	9	2003 *(2)*	Wales
Cemmaes Windfarm Ltd	Cemmaes	wind	15	2002 *(2)*	Wales
Fenland Windfarms Ltd	Red Tile	wind	24	2007	East Midlands
Fenland Windfarms Ltd	Deeping	wind	16	2006	East Midlands
Fenland Windfarms Ltd	Glass Moor	wind	16	2006	East Midlands
Fenland Windfarms Ltd	Red House	wind	12	2006	East Midlands
RES-Gen Ltd	Black Hill	wind	29	2006	Scotland
Airtricity	Tappaghan	wind	20	2005	Northern Ireland
Centrica (continued)	Glens of Foundland	wind	26	2005	Scotland
Haverigg III Ltd	Haverigg III	wind	3	2005	North West
HG Capital	Tyr Mostyn & Foel Goch	wind	21	2005	Wales
K/S Winscales	Winscales 2	wind	7	2005	North West
Paul's Hill Wind Ltd	Paul's Hill	wind	64.4	2005	Scotland
Scottish & Southern Energy plc	Artfield Fell	wind	20	2005	Scotland
Scottish & Southern Energy plc	Hadyard Hill	wind	120	2005	Scotland
Airtricity	Ardrossan	wind	24	2004	Scotland

E.On UK	Hare Hill	wind	5	2004	North East
E.On UK	High Volts	wind	8	2004	North East
E.On UK	Holmside	wind	5	2004	North East
Rothes Wind Ltd	Rothes	wind	51	2004	Scotland
Scottish & Southern Energy plc	Spurness	wind	8	2004	Scotland
Scottish Power	Cruach Mhor	wind	30	2004	Scotland
Crystal Rig Windfarm Ltd	Crystal Rig Windfarm	wind	50	2003	Scotland
RES-Gen Ltd	Forss	wind	2	2003	Scotland
RES-Gen Ltd	Altahullion	wind	26	2003	Northern Ireland
E.On UK	Bowbeat	wind	31	2002	Scotland
E.On UK	Out Newton	wind	9	2002	Yorkshire and
Scottish & Southern Energy plc	Tangy	wind	13	2002	Scotland
Scottish Power	Beinn an Tuirc	wind	30	2002	Scotland
Beaufort Wind Ltd	Tow Law	wind	2	2001	North East
E.On UK	Deucheran Hill	wind	16	2001	Scotland
Beaufort Wind Ltd	Lambrigg	wind	7	2000	North West
E.On UK	Lowca	wind	5	2000	North West
RES-Gen Ltd	Lendrum's Bridge	wind	13	2000	Northern Ireland
Scottish Power	Dun Law	wind	17	2000	Scotland
Scottish Power	Hare Hill	wind	13	2000	Scotland
EPR Ely Limited	Elean	straw/gas	38	2001	East
Scottish & Southern Energy plc	Wheldale	mines gas	8	2002	Yorkshire and
RWE Npower Plc (continued)	Kielder	hydro	6	2006 (2)	Yorkshire and
RWE Npower Plc (continued)	Dolgarrog Low Head	hydro	15	1926/2002	Wales
RWE Npower Plc (continued)	Cwm Dyli	hydro	10	2002 *(2)*	Wales
RWE Npower Plc (continued)	Dolgarrog High Head	hydro	18	2002 *(2)*	Wales
RWE Npower Plc (continued)	Inverbain	hydro	1	2006	Scotland
Scottish & Southern Energy plc	Fasnakyle Compensation Set	hydro	8	2006	Scotland
RWE Npower Plc (continued)	Braevallich	hydro	2	2005	Scotland
RWE Npower Plc (continued)	Garrogie	hydro	2	2005	Scotland
Scottish & Southern Energy plc	Kingairloch	hydro	4	2005	Scotland
Scottish & Southern Energy plc	Cuileig	hydro	3	2002	Scotland
Baglan Generation Ltd	Baglan Bay	gas turbine	575	2002	Wales
RWE Npower Plc (continued)	Little Barford GT	gas oil	17	2006	East
Immingham CHP LLP	Immingham CHP	gas CHP	741	2004	Yorkshire and
Gaz de France	Shotton	gas CHP	180	2001	Wales
	Aberdare District Energy	gas	10	2002	Wales
Scottish & Southern	Chippenham	gas	10	2002	South

Energy plc					West
	Bridgewater District Energy	gas	10	2000	South West
	Sevington District Energy	gas	10	2000	South East
	Solutia District Energy	gas	10	2000	Wales
Scottish & Southern Energy plc	Arnish	diesel	3	2001	Scotland
Uskmouth Power Company Ltd	Uskmouth	coal	393	2000	Wales
Coolkeeragh ESB Ltd	Coolkeeragh	CCGT	408	2005	Northern Ireland
Spalding Energy Company Ltd	Spalding	CCGT	860	2004	East Midlands
Premier Power Ltd	Ballylumford C	CCGT	616	2003	Northern Ireland
Coryton Energy Company Ltd	Coryton	CCGT	732	2001	East
RWE Npower Plc (continued)	Great Yarmouth	CCGT	420	2001	East
International Power	Saltend	CCGT	1,200	2000	Yorkshire and
Scottish & Southern Energy plc	Fife Power Station	CCGT	120	2000	Scotland
Scottish Power	Damhead Creek	CCGT	792	2000	South East
Scottish Power	Shoreham	CCGT	400	2000	South East
Seabank Power Limited	Seabank 2	CCGT	410	2000	South West

Table D.1 Operational power stations in the U.K. as of 2007

Recent Decisions On Applications (BERR 2008)

DATE OF DECISION	COMPANY / LOCATION	TYPE OF PROJECT/CONSENT REQUESTED	MAXIMUM OUTPUT
07/04/2008	Pulse Tidal Limited, Upper Burcom, River Humber	Tidal power generator/TWA Order	0.15MW
28/02/2008	Dong Energy - Gunfleet Sands II	Offshore wind farm - Section 36	64MW
28/02/2008	Renewable Energy Systems Ltd, Keadby, North Lincolnshire	Onshore wind farm - Section 36	85MW
28/02/2008	E.ON UK Renewables Ltd, Tween Bridge, Thorne, South Yorkshire	Onshore wind farm - Section 36	66MW
19/12/2007	Barking Power Ltd, Barking Power Station, Dagenham	CCGT extension	470MW
21/11/2007	Prenergy Power Ltd, Port Talbot	Biomass Plant	350MW

07/11/2007	DONG Walney Ltd Walney	Offshore wind farm	600MW
30/10/2007	EDF Energy West Burton Power Stations, Nottinghamshire	CCGT	1,270MW
16/10/2007	E.ON Drakelow Power Station South Derbyshire	CCGT	1,220MW
09/10/2007	Devon Wind Power Ltd, Fullabrook Down, North Devon	Onshore wind farm - Section 36	66MW
17/09/2007	SWRDA Wave Hub, off North Cornwall	Wave Energy	20MW
17/09/2007	EDF (Northern Offshore Wind) Ltd	Offshore wind farm - Section 36	100MW
19/02/2007	Greater Gabbard Offshore Wind Ltd, Outer Thames Estuary	Offshore wind farm - Section 36/36A	500MW
09/02/2007	Ormonde Energy Ltd, East Irish Sea	Offshore wind farm - Section 36/36A	100MW
18/12/2006	Thanet Offshore Wind Ltd, Outer Thames Estuary	Offshore wind farm - Section 36/36A and deemed planning	300MW
18/12/2006	London Array Ltd, Outer Thames Estuary	Offshore wind farm - Section 36	1,000MW
31/10/2006	E.ON UK Plc, New Isle of Grain Power Station, Kent	CCGT	1,260MW
21/08/2006	Severn Power Ltd Uskmouth nr Newport	CCGT	800MW
01/08/2006	Conoco Refinery (Immingham CHP), South Killingholme	CHP CCGT extension - Section 36	1,230MW
15/06/2006	Belvedere, Kent	Energy from waste - Section 36	70MW
19/04/2006	Fiddler's Ferry, Warrington	Retrofit of FGD plant - Section 36	
12/01/2006	Didcot B, Oxfordshire	Increase in generating capacity - Section 36	120MW
18/10/2005	Npower Renewables Ltd,	Onshore wind farm - Section 36	78MW

	Little Cheyne Court, Walland Marsh, Kent		
25/05/2005	Scout Moor Wind Farm Ltd, Scout Moor, Lancashire	Onshore wind farm - Section 36	65MW
03/03/2005	Corus Strip Products UK, Corus Steel Works, Port Talbot	Turbo-Alternator Extension - Section 36	20MW
11/11/2004	RWE Npower plc, Little Barford Power Station, Bedfordshire	OCGT Black Start	20MW
17/06/2004	RWE Innogy plc, Aberthaw Power Station, South Glamorgan	Retrofit of FGD plant - Section 36	1,500 MW
18/03/2004	EDF Energy (Cottam Power) Ltd, Nottinghamshire	Retrofit of FGD plant - Section 36	2,000 MW
21/01/2004	Rugeley Power Ltd - Rugeley Power Station	Retrofit of FGD plant - Section 36	1,000 MW

Table D.2 Recent decisions of application approvals 2008

Calculating the OM

Using the"Average load following" procedure:

Data until end of December 2006	**MW**	**GWh**	**Calculated capacity factor**
Major power producers *(1)*			
Total transmission entry capacity	**75,016**	344,584	
Of which:			
Conventional steam stations+CHP:	**33,628**	**151,512**	**51.4%**
Coal-fired	22,902r	138,965	69.3%
Oil fired	3,778	2,297	6.9%
Mixed or dual fired	8,392r	10,250	13.9%
Gas turbines and oil engines			
Combined cycle gas turbine stations	**24,859**	**116,398**	**53.5%**
Nuclear stations	**10,969**	**69,237**	**72.1%**
Hydro-electric stations:	**4,020**	**7,436**	**21.1%**
Natural flow	1,294	3,714	32.8%
Pumped storage	2,726	3,722	15.6%
Renewables other than hydro	**96**	**-**	
Other generators			

Total capacity of own generating plant	**8,029**	35,175	50.0%		
Of which:					
Conventional steam stations	**3,626**	**19,421**	**61.1%**		
Combined cycle gas turbine stations	**2,200**	**10,657**	**55.3%**		
Hydro-electric stations (natural flow)	**130**	**865**	**75.9%**		
Renewables other than hydro	**2,073**	**4,232**	**23.3%**		
All generating companies					
Total capacity	**82,641**	379,759	52.5%		
Of which:					
Conventional steam stations	**38,294**	**168,980**	50.4%	**normalised GW**	**Ranking**
Coal-fired	24,678r	142,681	**66.0%**	16.3	**2**
Oil fired	4,299	4,271	**11.3%**	0.5	**9**
Mixed or dual fired	8,913	22,028	**28.2%**	2.5	**7**
Gas turbines and oil engines					
CHP	404	1,954	**55.2%**	0.2	**4**
Combined cycle gas turbine stations	**27,059**	**127,055**	**53.6%**	14.5	**5**
Nuclear stations	**10,969**	**69,237**	**72.1%**	7.9	**1**
Hydro-electric stations:	**4,150**	**8,301**	**22.8%**		
Natural flow	1,294	4,579	36.7%	0.5	**6**
Hydro-electric stations (natural flow)	130				
Pumped storage	2,726	3,722	15.6%	0.4	**9**
Renewables other than hydro	2,169	4,232	**22.3%**	0.5	**8**
Imports	2,000	10,282	**58.7%**	1.2	**3**
	inc imports	390,041	Total	44.5	

Table D.3 Data on U.K. power stations and relative ranking

“Average marginal emissions” procedure

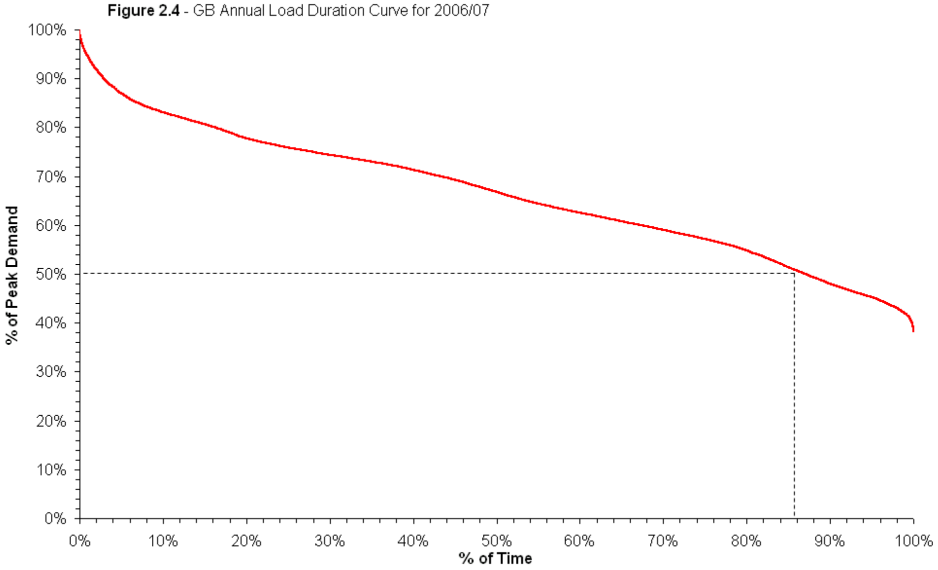

Figure D.1 Load duration curve for the UK grid 2006/2007

As the above grid was given in percentage format, the axes were modified to make it consistent with the aims of this work. As such, the x-axis was converted into hours with 100% time representing the 8760 hours available in a year, and the y-axis was modified so that 100 of peak demand equated to the 2006/2007 peak demand of 58.4 GW. For simplification, the above graph was treated as two distinct areas, a rectangular area with y values ranging from 0 GW to the beginning of the curve (approximately 23.4 GW) and the rest of the area that was under the curve. The curve was then approximated using a 3rd order polynomial equation, as can be seen in the next graph.

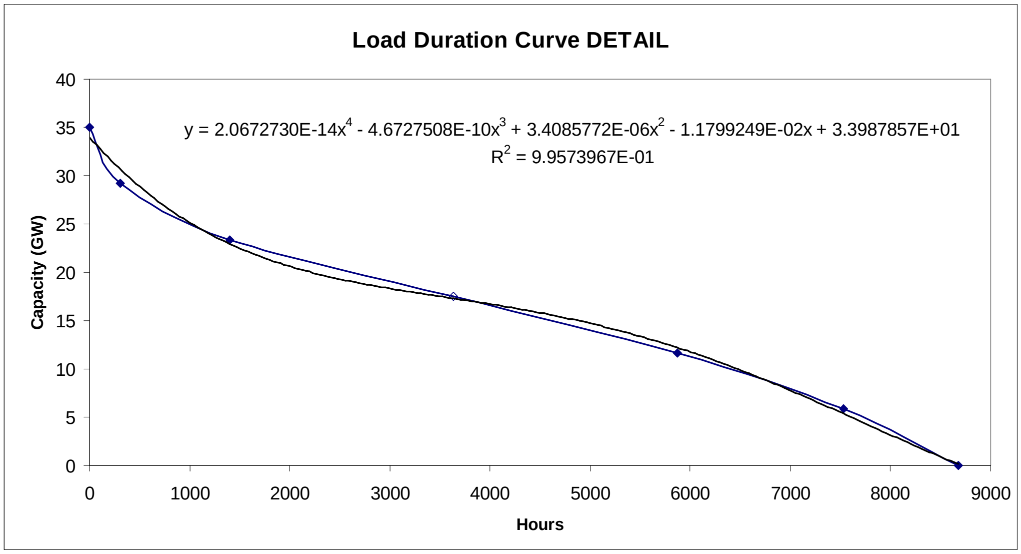

Figure D.2 Load duration curve detail and approximation

As can be seen from the R^2 value on the graph, the curve fit is almost 99.6%, so this curve approximations was deemed a close enough representation of the real curve. By integrating the above polynomial it was found that the area under the graph was approximately 184.863 GWh. This then meant that the "rectangular" section of the graph contained the remaining 205,178 GWh (since the total area under the load-duration curve was established to be 390,041 GWh). Using these values, it was then possible to construct a table and calculate the amount of time each power plant type spent intersecting the load duration curve (thereby staying at the margin).

	MW	GWh	Cumul. GWh	Cum. GWh under curve	Hours	GW
Nuclear stations	10969	69237	69237	-	8760	7.9
Coal-fired	24678.5	142681	211918	-	8760	23.2
Imports	2000	10282	222200	17022	8125	26.0
CHP	404	1954	224154	18976	8055	26.3
Combined cycle gas turbine stations	27059	127055	351209	146031	1618	45.3
Hydro-electric stations: nat. flow	1424	4579	355787	150609	1396	46.3
Gas turbines/oil engines/mixed use	9316.8	22028	377815	172637	444	52.7
Renewables other than hydro	2169	4232	382048	176870	284	54.3
Pumped storage	2726	3722	385770	180592	149	55.7
Oil fired power stations	4702.8	4271	390041	184863	0	57.3

Table D.4 Data on U.K. power stations and relative ranking

As can be seen from the final result of the above table, the calculated total demand is approximately 1GW less than the real value of 58.4GW. This however is a result of the rounding errors and the approximation of the load duration curve. However is felt that since the error is within 2% of the real value, the approximation is acceptable. With the above data it was then possible to build a picture of how each power plant type intersects the load duration curve, and can be seen below in Figure D.3 and D.4, while a more explanatory visual representation is given in the following graph:

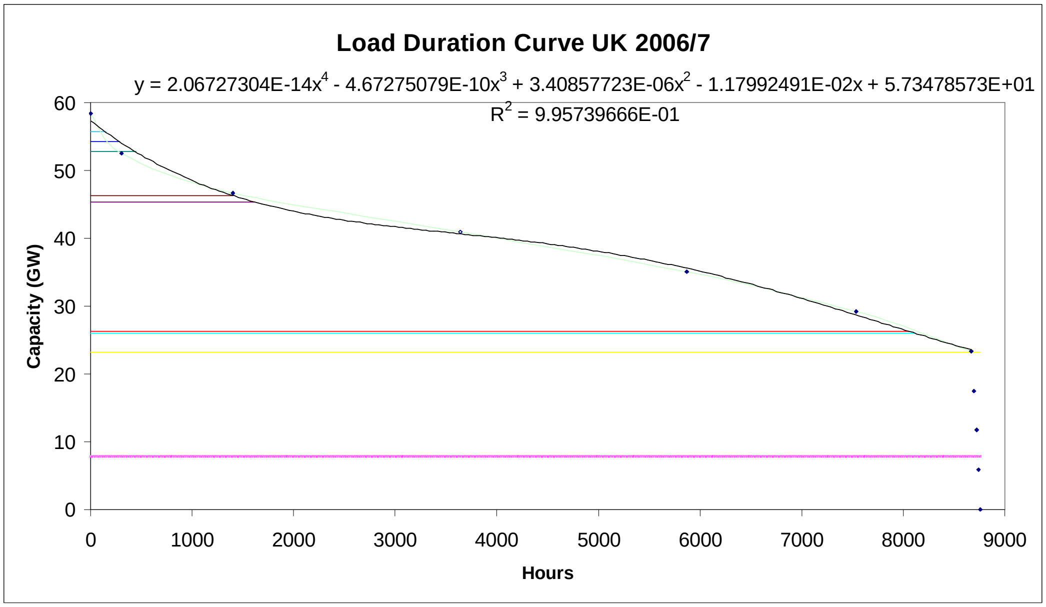

Figure D.3 Load duration curve approximation and power plant type curve intersections

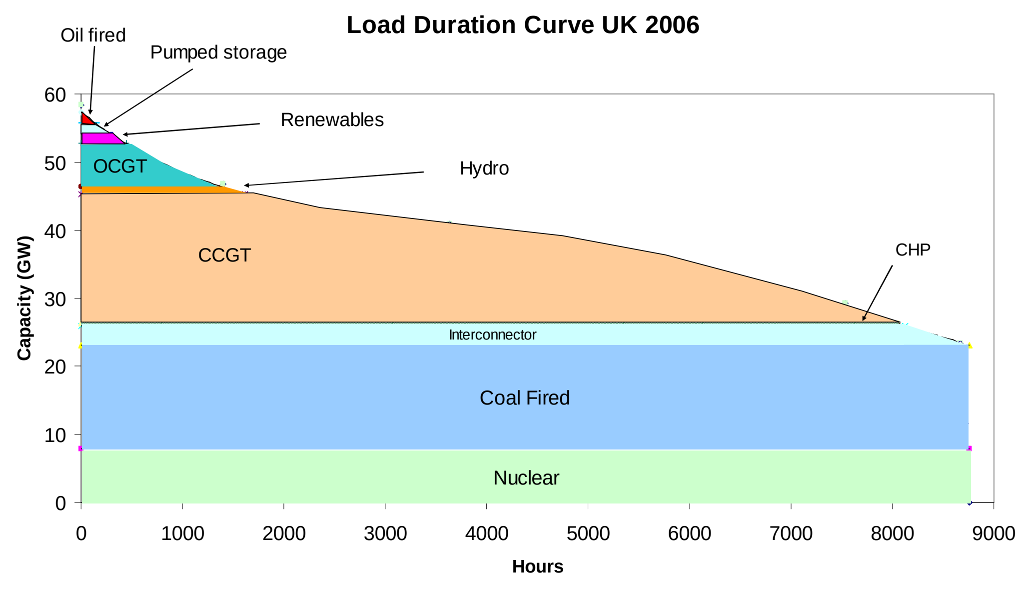

Figure D.4 Load duration curve with generation per plant type "slices" for 2006/2007 in the U.K.

Using the data behind the above graph, it was possible to then calculate the time periods for which each type of plant operated at the margin and by multiplying this with the emission factor for that type of plant, the average OM emission factor could be calculated. The table below gives an analytical review of this calculation:

	Hours	Hours on margin	emission factor gCO_2/kWh
Nuclear stations	8760.0	-	
Coal-fired	8760.0	392.9	880
Imports	8124.7	635.3	264.24
CHP	8055.4	69.3	550.5
Combined cycle gas turbine stations	1617.9	6437.5	440.4
Hydro-electric stations: nat. flow	1396.4	221.5	0
Gas turbines/oil engines/mixed use	444.2	952.2	862.45
Renewables other than hydro	283.8	160.4	0
Pumped storage	148.6	135.2	0
Oil fired power stations	0.0230	148.6	807.4

Table D.5 Hours of marginal operation and associate emission factors