

# **Carbon Assessment of Wind Power**

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## **ABSTRACT**

The Earth is facing huge implications from Anthropogenic Global Warming and peaks in the production of finite fossil fuels. Decision-makers have to choose strategies for combating these dual problems whilst ensuring minimal costs to society and the environment. Unfortunately, renewable technologies in particular have doubt associated with their ability to reduce total life cycle greenhouse gas (GHG) emissions of electricity due to uncertainty in estimates. This thesis analyses historic associated GHG estimates of wind farms, the largest renewables contributor to electricity generation in the UK, to reduce the uncertainty inherent in estimates and better understand critical factors that influence estimation. Through harmonisation of published life cycle GHG emissions estimates, they are reduced by 56% to between 2.9 and 37.3gCO<sub>2</sub>e/kWh. Average values for onshore and offshore wind power are calculated as 16 and 18.2gCO<sub>2</sub>e/kWh respectively and exhibit similar characteristics in their life cycle GHG emissions. Ormonde Offshore Wind Farm is analysed using a novel hybrid approach and gives total baseline GHG emissions of 17.5gCO<sub>2</sub>e/kWh and is the largest wind power installation to be analysed to date. Finally, an estimate of the effect of load variability of wind on thermal plant in the UK system is calculated. It is shown that this effect may reduce the net emissions saving from wind power relative to the whole UK system's savings when wind power is included.

## **DEDICATION *(if any)***

I dedicate this to everyone along the way who has put up with me during this PhD. This includes my Supervisors, Dr Edward Owens and Prof Susan Roaf who have put up with my eternal procrastinations, to my informal third supervisor and Internal Examiner Dr Gillian Menzies who has helped throughout for sound advice and expertise. I would also like to thank Dr Gabriela Medero for allowing me to work on a fantastic research project in a great team. To my family, Roger, June, Marcus and Melly (and now Affie!) who have managed to believe, or at least trust when I say I would someday submit. To my girlfriend Sarah Drummond who has shown unwavering support. To my friends who have made a suitable running joke of how not to ask how my PhD is going. Finally I dedicate this to my fellow students at Heriot-Watt for being there for coffee and conversation when needed. I will not forget this experience!

## **DECLARATION STATEMENT**

*(Research Thesis Submission Form should be placed here)*

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## PUBLICATIONS

Owens, E.H. & Chapman, S., 2013. Valuing the Greenhouse Gas Emissions from Wind Power. *International Journal of Energy Engineering*, 3(2), pp.41–54.

Owens, E.H., Chapman, S. & Allan, P., 2010. The impact of Carbon Capture and Storage on Coal Resource Depletion. *Energy & Environment*, 21(8), pp.925–936.

Full versions of publications are given at the end of this thesis.

## **Chapter 1 – Introduction**

This Chapter outlines the background and motivation for this project and provides objectives of the research, including how this will be presented. Some of the challenges addressed are presented, as well as a chapter outline of the thesis.

### **1.1 Background and Motivation**

Although intense debate continues concerning the likely scale of the effects, there is now little doubt in the Scientific Community that climate change is being caused by man-made greenhouse gas (GHG) emissions. In countries across the globe, one of the largest contributors to these GHG emissions is electricity generation and in the UK for instance, this contribution to total GHG emissions was estimated to be 33% in 2012 from power plants (DECC 2013). Associated GHG emissions arise through the direct use of fossil fuels, both in the manufacture and construction of the infrastructure, during the lifetime of fossil fuel burning in thermal power plants and also in their decommissioning. Reports by bodies such as the United Nation’s Intergovernmental Panel on Climate Change (IPCC) have highlighted a number of electricity generation technologies that are capable of providing electricity with low associated GHG emissions. However, some would argue that deployment of these technologies has been not rapid enough to affect a reduction in the potential impacts of Anthropogenic Global Warming (AGW) or it has been too heavily focussed on technologies not well suited to reducing overall associated GHG emissions.

The nature of the debate outlined above has left those who decide on policy with a confused picture. Clearly, this is not in the best interests of decision-makers and in some instances may have led to a rushed attempt at persuasion by scientists involved. A reduction in fossil fuel requirements throughout the global economy could only lead to a long-term security that is in doubt at present. There has been little or no common ground and an acceptance of more real, short-term goals could ultimately reward all parties. The very real threats of Peak Fossil Fuel Production gives this opportunity that can be grabbed by all parties and used in a much more diverse way than AGW has been so far. The current EU legislations that have shaped UK legislation are focussed on the production of emissions. Based on the evidence presented in Chapter 2, it should be considered unacceptable to only consider these emissions without also including the consumption of carbon-rich products. The best course of action for the UK is one of whole life cycle thinking of available technologies in order to understand and reduce the

resource costs of energy projects in relation to this thesis. This is since electricity and its associated resource costs feeds into every aspect of the UK economy.

Another equally serious problem for regions is the availability of fossil (and other non-renewable) fuels due to both localised supply issues and apparent peak production issues globally, referred to in the previous paragraph as Peak Fossil Fuel Production. These peak production issues will be further expanded on in Chapter 2, as they appear to offer an equally serious situation for decision-makers and have direct implications for electricity generation that is intrinsically linked to fossil fuel use. However, as with AGW, this is an equally debated topic with a number of commentators still refusing to acknowledge this inherent problem with relying on a finite resource such as fossil fuels. Since these two global issues can be related to the same addiction, methods of reducing this need are being sought.

Wind power's contribution to global electricity production is set to continue to grow rapidly over the coming years and can be seen as one of the first large-scale renewable technologies to impact electricity supply networks through extensive deployment, particularly in Northern Europe. At the end of 2011 it was reported by the Global Wind Energy Council (offshorewind.biz 2012) that the total capacity stood at 93,957MW within the EU. It has also been reported that based on the rate of deployment of the technology recorded in 2010, EU targets of 20% renewables by 2020 should be exceeded by 0.7% (GWEC 2010).

The growth of any technology requires considered planning, based on its intended purpose. In this case, renewable electricity production technologies such as wind farms are being commissioned in order to reduce the GHG emissions associated with large-scale regional electricity production and reduce a region's dependence upon depleting fossil fuels, while ensuring security of supply of electricity. It is this ability (or lack of) to reduce GHG emissions through using fewer fossil fuels that must be assessed in order to take the appropriate course of action.

## **1.2 Research Challenge**

Global progress towards reducing GHG emissions has so far been seen as ineffective and too slow to hit IPCC targeted goals for ensuring least detrimental damage to the

planet. This issue can be highlighted locally in that total UK GHG emissions have in fact increased over the period 1993-2010 by 9% if consumption of goods and services are considered rather than simply domestic production (Scott et al., 2013; Table 2). The lack of global agreement on reducing GHG emissions will continue to erode any reduction within individual regions, especially if production can simply be re-located. Ignoring political intricacies, there are still doubts over the technologies themselves. The overarching challenge for this thesis is to reduce the doubt over published information on the life cycle estimates for associated GHG emissions of technologies such as wind power and suggest an approach to estimating these emissions that does not contain the same level of uncertainty. Among possible reasons for doubt is uncertainty over the ability of these technologies to effectively reduce total associated GHG emissions from electricity generation. With large ranges of estimates of GHG emissions for some technologies, or very few estimates for others, it can be difficult for decision makers to decide the best course of action that will decarbonise electricity sufficiently enough to cause effective change while still providing secure supply at affordable costs to society.

In terms of the type of electricity generation technologies that will predominantly make up the UK energy mix, life cycle GHG assessment will become increasingly important to track indirect emissions due to the characteristics of low carbon technologies having relatively low environmental impacts in the use phase of their life cycles, but relatively large associated GHG emissions in their manufacture and construction. Renewables, namely wind power in this instance, may be able to provide the targeted 2020 electricity generation contributions for the UK. Life cycle GHG assessment could be used to effectively estimate environmental impacts and associated GHG emissions. Without a secure energy future, there will be less economic ability of a country or region to afford to reduce GHG emissions, assuming that externalities are not part of the overall costing.

This thesis will introduce life cycle GHG estimation for products and services in Chapter 4. Current literature around life cycle studies will be outlined and specifically, the International Standards Organisation (ISO) Life Cycle Assessment (LCA) framework will be reviewed. In order to confidently compare technologies and aspects of their life cycle, a well understood standard assessment method must be in place for decision-makers. It is suggested in this thesis that historic life cycle studies should be assessed based on their system boundaries, the assumptions made, the data used, the

ability to utilise the GHG emissions figures for reduction, the methods of displaying uncertainties in the results and their transparency throughout the assessment process. The fundamental importance of standardising the life cycle GHG assessment methodology will be clearly shown, since key problems within the ISO LCA framework still exist. These need to be understood before a methodology can be formalised to assess technologies that are being used in the power sector.

Given that wind power's contribution to electricity generation is increasing, its relative capacity credit may be decreasing and it should be recognised that a diverse electricity mix is of crucial importance to avoid over-reliance on one type of technology. It does not seem feasible or cost effective to attempt to meet all electricity targets with only wind or a similarly intermittent technology. Wind power's effectiveness in reducing total GHG emissions associated with the whole electricity network should be well understood. Simply deploying wind power in the UK has so far not resulted in equivalent reductions in the overall GHG intensity of UK electricity and this must be of concern moving forward if not properly understood. The challenges and opportunities relating to the UK's requirement for a large new contribution to installed capacity due to the retirement of much of the current generation capacity also adds another dimension to this issue.

It should be noted that life cycle GHG assessment is not the only solution to determining opportunities to reduce national and global GHG emissions. It will be shown that the development of the International Standards Organisation's (ISO) life cycle assessment LCA methodology (ISO 14040-44) has led to acknowledgement of a number of common problems within the framework that can be discussed and reduced in relation to specific scales and technologies within a sector. The goal of using this set of common problems to critique historic LCAs and life cycle GHG assessments seems reasonable, especially since fewer problems tend to lie at the technology scale (will also be referred to as 'micro scale' in Chapter 4) in this instance.

Even with a formalised methodology for a given technology, a large range of estimates of associated GHG emissions may exist. Published life cycle GHG emissions of wind power systems have a large range from 2 to 81gCO<sub>2</sub>e/kWh, as will be seen in Chapter 5. While this could be considered a small absolute range for a power generation technology, it represents a difference of almost two orders of magnitude from the

smallest to the largest value. This range needs to be made smaller if possible through applying a harmonisation process that assesses inherent sensitivities in estimation and adjusts them, based on understanding from reviewing all estimates together. This is important for decision-making. Harmonisation of life cycle GHG emission estimates is shown to decrease the variability of estimates and offers a methodology for better understanding critical factors that affect the assessment of associated GHG emissions for a given technology. This was developed by the National Renewable Energy Laboratory (NREL) and will be replicated, while including more recent GHG estimates.

With offshore installations currently being the fastest area of development in wind power, particularly in Northern Europe, more studies are required to further support their development. In particular, the additional life cycle stages involved with offshore installations such as the civil works required for grid connection and power transmission should be considered to align GHG estimation with development in the wind industry. Chapter 6 offers a case study of Ormonde Offshore Wind Farm in order to offer an estimate of associated GHG emissions for an offshore wind installation. This is an estimation of one of the largest offshore sites to date, with installed capacity of 150MW.

The true total life cycle GHG emissions that can be attributed to the Ormonde Offshore wind farm project will be shown to lie within the range given previously. It is impossible to know exactly what the true estimate is but by highlighting the various issues in estimating this figure, it can be seen that some assumptions made by the assessor are more important than others. These will become ever more apparent as more life cycle studies are published but through a harmonisation study in Chapter 5, and Chapter 6's case study, it will be clearly seen that hybrid analyses, while offering relatively higher estimates, also include far more of the project's stages than either the process or cost-based analyses. While this is intuitive, it should also be seen that the perceived complexity of hybrid analyses could be reduced through further research into cost breakdowns of wind farms (as well as other technologies) and the allocation of these costs across the lifetime of a wind farm. Decision-makers should be wary of any life cycle estimate that does not make it clear which critical factors (predominantly capacity factor and lifetime in the case of wind power) are chosen and why, along with methodological choices for recycling and dataset choices. The clearer the life cycle

study is on the critical factors it assumes, the easier it is for a decision-maker to see the possible range on which to base future decisions.

An important element of historic life cycle studies into wind power installations is lacking. This is the likely effect of wind power to an electricity network, such as that found in the UK, where traditional thermal power plants are also contributing to total generation and the dynamics of their interaction requires greater understanding. In particular the effects of intermittency on the efficiency of thermal generation plants should also be studied further due to wildly conflicting estimates of the adverse effects of this intermittency.

This will be discussed in Chapter 7 in order to attempt to assess whether intermittent power generation has a detrimental effect on the efficiencies of the traditional power plant fleet. There is an effect by the load variability of wind on thermal plants in the same system that reduces the net emissions saving from wind power. Commentators suggest wildly differing estimates so an estimate is suggested here that incorporates harmonised life cycle GHG estimates for wind power with previous studies that utilise published carbon intensity factors for the other UK technologies, as well as efficiency curves for UK thermal plant technologies. As the installed capacity of wind increases – and hence the reduction in residual load factor felt by the thermal plants on an electricity network – this net saving will be further reduced. There are also numerous other factors influencing thermal plant efficiencies that should be better understood.

It should be stated that it is not the intention of this thesis to review short-term changes to the electricity mix and how this affects the relative GHG intensity at a given time. This thesis will focus on those total life cycle GHG emissions that can be assigned to wind power's whole life cycle. These short-term characteristics have been captured in Chapter 7's analysis of load variation resulting from wind power's generation profile and are not considered to any greater depth.

### **1.3 Hypothesis**

This thesis aims to reduce the uncertainty in carbon assessment of wind power technologies. Life Cycle Assessment is a route to better understanding the carbon outcome of wind technology in an electricity network.

## **1.4 Objectives**

- a) Review all historic estimates of associated life cycle GHG emissions of wind farms that are publically available
- b) Conduct a full life cycle GHG assessment of Ormonde Offshore Wind Farm in the Irish Sea in order to provide an estimate and range of life cycle GHG emissions.
- c) Develop a hybrid assessment methodology that reduces uncertainty in GHG estimation of large-scale wind power technologies and provides an estimate of associated GHG emissions of all parts of the project.
- d) Estimate the impact of the load variability of wind power on thermal power plants in the UK electricity supply network that reduces the net emissions saving from wind power

## **1.5 Outline of Thesis**

This thesis is organised as set out below and includes references in a single list at the end.

Chapter 1 outlines the background, motivation, specific research challenge faced and outputs of this research.

Chapter 2 outlines the requirement for decarbonising electricity generation by reviewing the need to account for carbon, based on scientific debate in relation to AGW and peak production of fossil fuels.

Chapter 3 looks at the energy sector in the UK in relation to the electricity mix, how it has changed and is likely to change, and the likely contribution of wind power to the total generation capacity.

Chapter 4 assesses the current state of GHG accounting in all sectors in order to learn from the experience of the progression of the International Standards Organisation's (ISO) Life Cycle Assessment (LCA) methodology for products and services.

Chapter 5 conducts a statistical review (META-Analysis) of a large number historic life cycle GHG estimates that are publically available in order to determine critical factors



affecting the estimation of life cycle GHG emissions associated with wind power specifically.

Chapter 6 presents a case study of 150 MW Ormonde Offshore Wind Farm in the Irish Sea. This study conducts a process-based analysis and a cost-based analysis that results in the formulation of a hybrid analysis of the wind farm.

Chapter 7 assesses the impact of load variability of wind power on thermal power plants in the UK electricity supply network since this has been suggested as causing a reduction in the net emissions saving from wind power.

Chapter 8 presents results from the thesis as a whole and offers conclusions to these results. Areas of further research are then suggested in order to further develop research in this field.

Specific to this thesis are the following contributions:

1. Another harmonisation study of historic wind power life cycle GHG estimates (Chapter 5)
2. A life cycle carbon assessment of a 150MW offshore wind farm, one of the largest sites to be assessed to date. (Chapter 6)
3. An analysis of how wind technology sits within the energy supply with an estimation of how intermittent electricity supply from wind power may affect other power plants on an electricity network (Chapter 7)

## **Chapter 2 – The Need to Account for Greenhouse Gas Emissions**

This chapter outlines key information that has shaped opinion and policy in relation to greenhouse gas (GHG) emissions and the accounting of them within industry, and more specifically, the UK energy sector. Firstly, brief coverage of the scientific debate on climate change and Anthropogenic (human-influenced) Global Warming (AGW) is presented that has led to the Intergovernmental Panel on Climate Change (IPCC) predictions of the impacts associated with AGW. Also, reasons are offered for some of the scepticism that still exists. The chapter also review the debate on the depletion of fossil (and other non-renewable) fuels in relation to the concept of peak production as a key component in the decision to account for resource use and associated carbon emissions. This latter area of resource use is perhaps not yet appreciated as big a problem as AGW by some but this chapter attempts to highlight its importance in driving energy policy alongside AGW. While AGW has become a heavily debated topic in the planning of future energy requirements of countries and regions, it will be argued that energy security will be driven by climate change policy, but even more dependent on the peak production of fossil fuels in the near future. This is seen in a greater interest in unconventional oil and gas reserves, driven by improving economic viability of exploiting these reserves. It could be argued that peak fossil fuel production issues are more tangible for organisations involved with fossil fuel production and consumption than issues of greenhouse gases currently are and so is more accessible for discussion. Indeed, with the large growth in the exploitation of unconventional oil and gas reserves, economic and environmental arguments for technology and resource planning are diverging. The UK may indeed have a policy on decarbonisation but if the purpose of this is solely to reduce GHG emissions then why does it allow exploration and licencing of new fossil fuel deposits?

### **2.1 The Science behind the Reasoning**

To understand why emissions should be accounted for, the scientific argument that led to legislation to reduce our emissions is briefly presented. It is not the intention of this thesis to attempt to prove or disprove such climate science, but rather to present it so as to explain the current rationale for reducing greenhouse gas emissions on a global scale, beginning immediately. It would be easier to simply present the climate projections that are summarised by the Intergovernmental Panel on Climate Change (IPCC) since numerous governments, especially those in the EU, have adopted their findings and

aligned their legislations surrounding GHG emissions reductions accordingly. However, it is the intention of this chapter to present these findings in a more detailed way, relating to their origins in order to better discuss them in relation to the thesis topic. This is because of the resistance from some in the scientific and professional community to these findings, leading to a slow global uptake in coherent policy. The doubts over the scale of AGW should be understood so that the resistance to policy change can be understood and so that uncertainty can be allowed for in policy issues. When discussed alongside peak production, the weight of AGW as the premise for carbon accounting could be seen to lessen. The objective of this discussion is to remove carbon accounting from a purely theoretical ideal of reducing emissions that are solely responsible for a change in climate that may to a greater or lesser extent be a result of human activities. The resulting message here is how we effectively monitor our carbon consumption as opposed to our carbon production (emissions). In other words, while current EU policy focuses on carbon emissions produced domestically, it will be seen that if the challenge of AGW is to be effectively addressed, carbon emissions embodied in all products and energy that are consumed by an economy must be known and accounted for.

The theories behind global warming, and attempts to understand it, have existed for a long time. However, some 95% of all published climate change science literature since 1834 was published after 1951 (Treat et al. 2007). Relative to the theory, advancements have been very recent in the expressed certainty of this science. The World Meteorological Organisation (WMO) and the United Nations Environmental Program (UNEP) founded the IPCC in 1988 in order to be a vessel by which climate science could be navigated. Another of its remits was to advise policy makers on an appropriate course of action.

The IPCC can be seen as the leading international body for the assessment of climate change and it is only fitting to mention this body from the outset of this section on the science of climate change due to its standing within the scientific debate. Few other scientific fields have aroused such multidisciplinary discussions of the scale that climate change has. By its very nature, it concerns us all, regardless of the implications or projected impact. It is therefore in theory critical to have a body such as the IPCC in place to collate and present the scientific argument. Science relies on the presentation of findings and theories in order to provoke debate and testing of those theories in a structured and open manner. This structured approach is the backbone of academic peer

review and should allow all theories and views to be supported or contended. The IPCC, therefore, can be seen as the authority on climate science, presenting all the information objectively. In the IPCC's latest assessment report (AR5), the certainty that humans cause climate change has increased while their projected range of values has reduced. This is in response to the failure of the more recent projections to predict the recently observed pause in global temperature increases. It is important to understand these, and other current issues, in relation to forming policy around climate science. Since the science has set policy in the EU to dramatically reduce overall GHG emissions, it should be understood in order to better develop overarching agreement on further policies moving forward.

## **2.2 The Raw Data**

Climate can be defined as the “average weather” and described “in terms of the mean and variability of temperature, precipitation and wind” over any given period of time, whether that be as short as a month or as long as a millennia (Treut et al. 2007). The climate has changed throughout history and will continue to do so for as long as the Earth exists. These changes are due to the natural cycles of the Earth. This helps to explain climate change as presented in this thesis as it refers to the change in this average or mean trend of a period of time that is “unnatural”. Global Warming is an averaged warming of surface and sea temperatures around the Earth from these unnatural changes.

The debate on AGW began as a result of studies conducted by Charles David Keeling at Mauna Loa in Hawaii from 1959. He was able to measure carbon dioxide concentrations in the air in such a way as to “maintain an accuracy and precision” that allowed for other scientists to distinguish between carbon dioxide from fossil fuel emissions and carbon dioxide that occurred in the natural cycle of the Earth. Mauna Loa is the world's biggest active volcano; meaning that 87% of Keeling's data had to, and still has to, be adjusted to compensate for the activity of the volcano. Later independent studies appear to validate Keeling's discoveries (Treut et al. 2007) and Keeling offers explanation of compensation for Mount Mauna Loa and justification of Hawaii as a test site (Keeling et al. 2009). The carbon dioxide record gave the first credible link between the increase in carbon dioxide levels and fossil fuel burning. However, the key to climate science is putting such research into the context of the Earth's natural cycle and historical trends. This was approached from the research done on ice-cores from

Greenland and Antarctica. The research provided data that spanned hundreds of thousands of years of history and showed a degree of variation in carbon dioxide levels. It was seen that large climatic events could occur rapidly, on a regional level at the least, and that the last 10,000 years, known as the Holocene – our interglacial period, has been an “exception, rather than a rule” (Dansgaard et al. 1993) in the sense that it has been very stable in terms of its climate. Further study highlighted that atmospheric carbon dioxide levels would fluctuate over the last 1,000 year period up until 50 years ago, in the order of  $280 \pm 10$ ppm (Indermühle et al., 1999). Whilst revealing that it was only part of the natural cycle that carbon dioxide levels in our atmosphere should fluctuate, it also showed that the levels now being recorded of 391 ppm in 2011 (IPCC 2013a) is significantly greater than have been seen in measurable history. This rise may seem logical due to our use of carbon-rich fuels since the Industrial Revolution, but it is the fact that it was now measurable in the context of the Earth’s natural cycles. For the sake of this thesis it is also important to note the other GHGs such as methane and nitrous oxides have had comparable increases in their atmospheric levels (Forster et al. 2007) in that they increased almost exponentially from the beginning of the Industrial Revolution.

What was missing from climate science, that would improve understanding of human impacts, was the impact of these GHGs on the climatic system. The link had to be made by viewing temperature records. Land temperature records have been recorded nearly as long ago as the thermometer’s invention in the early 1600s (Treut et al. 2007). However, there are four main obstacles to turning instrumental observations into accurate global time series in order to associate changes in temperature with other factors, such as the recorded rise in GHGs. These are stated by the IPCC, Section 1.3.2 (Treut et al. 2007).

1. Access to data in a useable form
2. Quality control to remove or edit erroneous data points
3. Homogeneity assessments and adjustments where necessary to ensure the fidelity (accuracy) of data.
4. Area-averaging in the presence of substantial data gaps.

It is not the case that temperature records are simply recorded and applied to the graphs and trends that are published today. The “adjustments” are numerous and so modelling

temperature is inherently complex in order to homogenise for the Earth. One of the main issues is how local factors affect the global temperature time series such as urban heat island contamination, land use change and how quality of data is maintained. This was addressed by contributors to the IPCC reports in two ways. Firstly, adjustments were made to the recorded temperature of measurement stations in urban areas to account for the assessed urban heat island effects. Secondly, analyses were performed in order to assess the extent to which urban heat island contamination affected temperature records (Treut et al. 2007). While the IPCC believes that the local effects are adequately accounted for, there are also challenges against the methods used in the decision-making process that included or disregarded certain land temperature records and locations. Some believe that about “half the post-1980 warming trend” can be explained through assessment of socioeconomic changes, such as urban heat island effects (Mckitrick 2007). This paper, and follow-up publications, by Mckitrick and others subsequently led to a lengthy dispute over evidence reported for the recorded rise in temperatures and will be further discussed in section 2.4. By the end of the 1800s, systematic observations of the weather were being made in a majority of the inhabited areas of the Earth (Treut et al. 2007) so temperature records were being created in numerous locations around the world. Some sceptics would go on to argue that some of the decisions taken to remove temperature records are for reasons that are not purely scientific – stations are chosen for the support of a pre-determined conclusion (D’Aleo & Watts 2010), although this is not a widely held view amongst climate scientists.

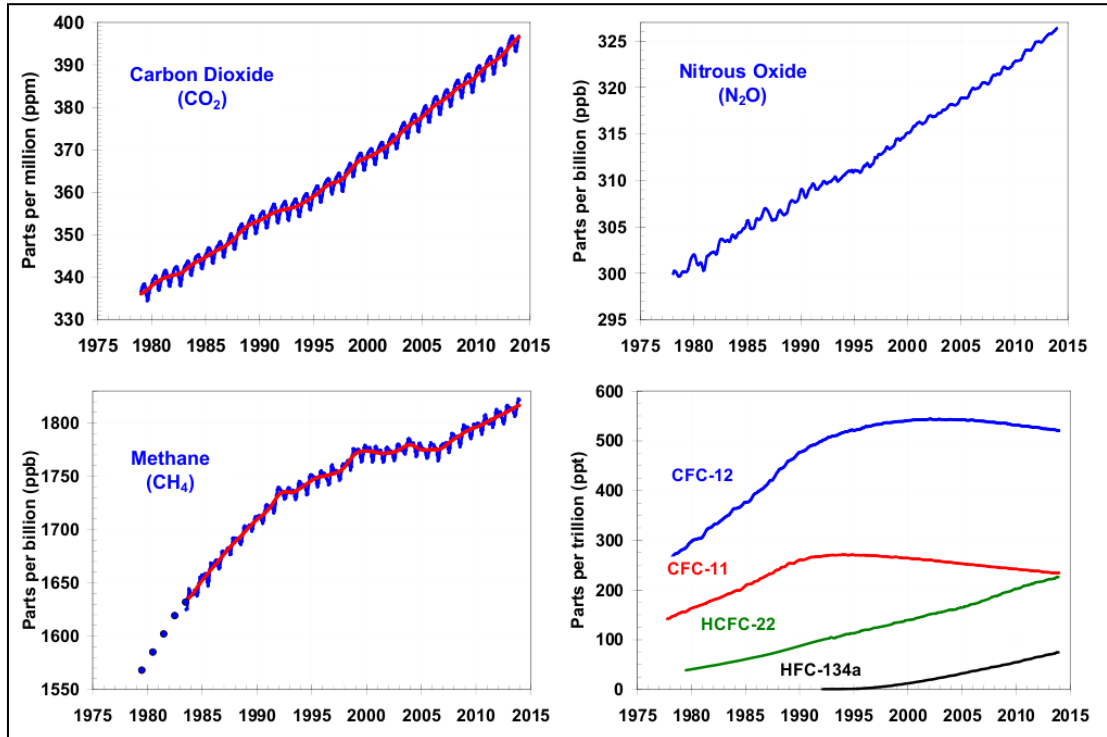
Another key set of data in identifying trends in our climatic system is ocean temperature data. This data has, in some form, existed since the middle of the 19<sup>th</sup> Century when shipping fleets began recording ocean temperatures by literally hoisting buckets of water aboard and adding a thermometer (Treut et al., 2007). These early measurements again would be subject to adjustment in order to align them with current observation techniques; such methods include over one thousand floating buoys that both drift and are in fixed locations in order to increase the coverage of temperature data since the historical shipping data is restricted to the main shipping lanes and fleets that were involved in taking temperature. The data sets have been brought up-to-date through adjustment and digitisation into the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and - unlike the land temperature data that has been criticised on some levels as discussed previously - is online and can be easily navigated in order to locate the archived data and is open to public and scientific scrutiny. This data source

goes as far back as October 1662, since it incorporates all available surface temperatures, both from land and sea. The Global Historical Climatology Network-Monthly (GHCN-M) raw data from January 1880 is also available from the National Climatic Data Centre, allowing for more transparent use of historic data. Since 1982, there has also been “near-global” coverage by satellite data, as stated by the IPCC, who go on to suggest that, even after adjustments of difference in techniques and the assessment of all available temperature time series in parallel, there has been a strong agreement in surface temperature data since 1900 (Treut et al. 2007).

### 2.3 Observations

The following section outlines some of the current observations and why they are adding to the debate over the IPCC’s projection accuracy.

The IPCC say that the largest component of observed warming is due to increases in anthropogenic GHG concentrations (IPCC 2013a). GHG Increases from the National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Gas Index show a relentless increase in these gases as Figure 2.1 shows:



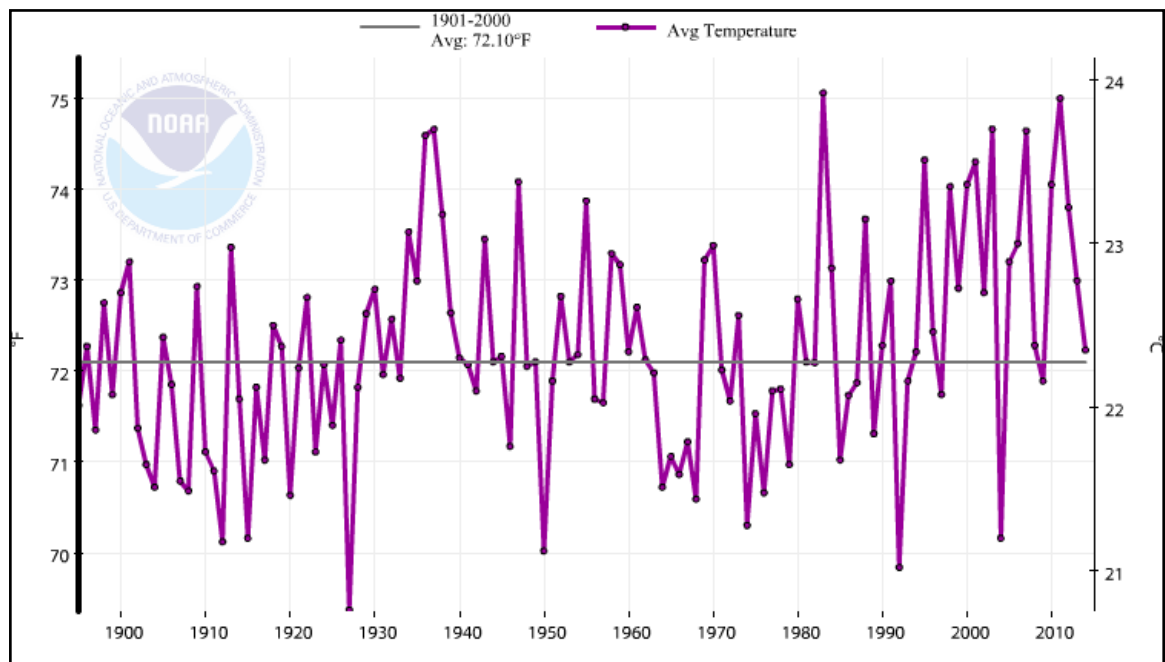
**Figure 2.1:** Global averages of the concentrations of the major, well-mixed, long-lived GHGs - carbon dioxide, methane, nitrous oxide, CFC-12 and CFC-11 from the NOAA global flask sampling network since the beginning of 1979 (U.S. Department of Commerce 2015).

**Carbon dioxide** is the most important anthropogenic GHG, according to the IPCC. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 391 ppm in 2011 (IPCC 2013a). CO<sub>2</sub> has accounted for nearly 80% of the increase in irradiative forcing that causes global temperature increases, according to the NOAA (~0.45 W/m<sup>2</sup>) (U.S. Department of Commerce 2015). **Methane** has increased from a pre-industrial value of about 715 ppb to 1803 ppm in 2011. **Nitrous Oxide** has increased from a pre-industrial value of about 270 ppb to 324 ppm in 2011 (IPCC 2013a).

The atmospheric concentration of carbon dioxide in 2011 exceeded by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores. The annual CO<sub>2</sub> concentration growth rate was larger during the 10 years (1995–2005 average: 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960–2005 average: 1.4 ppm per year) although there is year-to-year variability in growth rates. Annual fossil carbon dioxide emissions are at an average of 7.2GtC (26.4GtCO<sub>2</sub>) per year in 2000-2005. The observed global temperatures, as will be shown, have not followed such a steady trend. However, thirteen of the fourteen years in the range 1995–2009 rank among the warmest years in the instrumental record of global surface temperature (since 1850). 2008 was the coolest of the decade (NASA 2015). Relative to pre-industrial temperatures (1850), land and surface temperatures, taken from three main sources of satellite data (HadCRUT4 NOAA-NCDC and NASA-GISS) showed an average warming of 0.78°C. See Figure 2.3 for NOAA data from 1900-2014. The rate at which the global average temperature has changed over the last 140 years is mostly positive, but some comparatively short periods of negative changes also occur, such as from 1950 - 1975. The positive trends occur for relatively long periods and reach peak rates of rise of around 0.2 °C per decade. Whether this is true for thousand year time series remains in doubt; the discussion is not easily resolved as will be discussed. The average rise of 0.78°C was larger than the updated 100-year linear trend (1906 to 2005) of 0.74°C [0.56°C to 0.92°C] given in the IPCC's Assessment Report 4 (IPCC 2007) which was also larger than the corresponding trend for 1901 to 2000 given in the Third Annual Report from the IPCC (TAR) of 0.6°C [0.4°C to 0.8°C]. The linear warming trend over the last 50 years up to 2005 was (0.13°C [0.10°C to 0.16°C] per decade) which is nearly twice that for the last 100 years up to 2005. The total temperature increase from 1850–1899 to 2001–2005 was 0.76°C [0.57°C to 0.95°C]. Urban heat island effects are said to be real



but local, and have a negligible influence (less than  $0.006^{\circ}\text{C}$  per decade over land and zero over the oceans) on these values (IPCC 2007). We have already seen that this has been questioned in the published literature by some (Mckitrick 2007). There is consistent stability in the diurnal temperature range (DTR – the range between the coldest recorded temperature of the night and the hottest recorded temperature of the day) between 1979 and 2004, although it is said that trends are highly variable between regions. Temperature data comes from surface data that has been criticised, as discussed, but according to the IPCC, satellite and balloon born temperature data is similar and contains comparable uncertainty ranges. Since the IPCC’s first report in 1990, assessed projections gave global average temperature increases between  $0.15^{\circ}\text{C}$  and  $0.3^{\circ}\text{C}$  per decade for 1990 to 2005. This can now be compared with observed values of about  $0.2^{\circ}\text{C}$  per decade, strengthening confidence in near-term projections. This evidence appears to support the IPCC’s case for AGW. The more recent issue for the IPCC and those looking in on the debate has been mentioned that the previous decade shows a decrease in the rate of increase in surface temperatures to nearer  $0.038 - 0.059^{\circ}\text{C}$  (see Figure 2.4). It has been widely regarded that the rate of change in temperature of the main temperature reconstruction has essentially been zero for at least a decade.



**Figure 2.2:** Global Average Temperatures for from 1900 – 2014 from GHCN (NOAA - National Climatic Data Centre (U.S. Department of Commerce 2013).

The average temperature of the global ocean has increased to depths of 3000m. The ocean absorbs 80% of the heat added to the climate system. This has caused expansion of the ocean that has been responsible for around 57% of the observed sea level rise, the rest coming from glaciers and ice caps melting (28%) and the Greenland and Antarctic Ice Sheets (15%) - calculated from Table TS.3 (Solomon et al., 2007). It should be noted that there is also a slight difference between the individual contributions as shown here and the total observed sea level rise from satellite data. This leads to a difference of 0.3mm per year, equivalent to more than Greenland or the Antarctic contributions. The current rate of average sea level rise is now at 3.2mm per year, a rise of 0.1mm per year since the IPCC AR4 in 2007 (University of Colorado 2013).

#### **2.4 What is causing the recorded rises in temperature?**

What is happening to our climate and why is it happening? These are the fundamental questions that the climate sciences have been trying to answer for many years. The IPCC defines the data and the picture that it is conveying as the following:

Attribution of changes to human activities must be pursued by:

- Detecting that the climate has changed. *Detection* is defined as the process of demonstrating that the climate has changed in some defined statistical sense, without the provision of a reason for this change. This is the temperature time series that have come from adjustment of historical data and current data being recorded.
- Demonstrating that this detected change is consistent with computer models simulations of the climate change ‘signal’ that is calculated to occur in response to anthropogenic forcing, i.e. that forcing by human activity.
- Demonstrating that the detected change is not consistent with alternative physically plausible explanations of recent climate change that exclude important anthropogenic forcing.

(Treat et al. 2007)

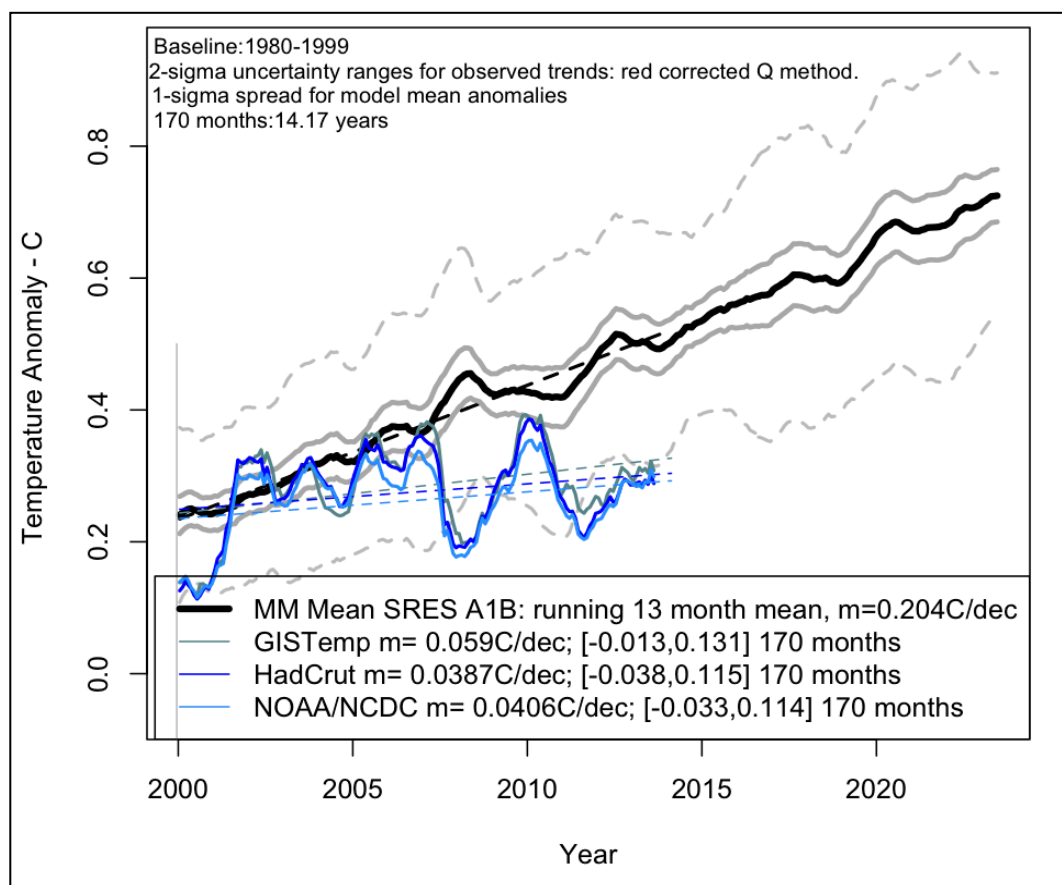
The detection and attribution of climate change rely heavily on the observed data and model output, as the above IPCC definitions highlight. By their own admission, it is very difficult to find trends in the observed temperature records that can be related to historical human habits and the “relatively short length of most observed records” in relation to the history of the Earth (Treat et al. 2007). However, the ability to model

complex systems has increased a large amount in recent years. From simple models being used in order to try to and assess the effects of changes in one variable in the climatic system, complex models now incorporate greater variables, such as precipitation, global pressure patterns and the analysis of vertical profiles of temperature changes in the oceans and atmosphere (Treut et al. 2007) and are referred to as Global Circulation models (GCM).

It is these GCM's that make it easier to attribute climate changes to human influence, rather than just the natural climate forcing that occurs, according to the IPCC, since only significant influence in the models from anthropogenic factors can cause the large changes that have been seen in the detected temperature changes (Treut et al. 2007).

This outcome from the models could be put down to how the complex climate scenarios are arranged in the models. No longer is climate change assessed by simply changing carbon dioxide levels in the models, but other factors are incorporated such as global land use and the addition of small particles into the atmosphere such as aerosols and clouds. It is clear from the modelling that even minute changes to the inputs to these models can have huge effects on the outputs. This has been compared to Chaos Theory by the IPCC. However, it is still considered more difficult to determine weather patterns past a week or so in the short-term. It is perceived by contributing scientists to the IPCC reports, who model the climate system, that long-term changes are more easily predicted than short-term patterns: *“Mathematics cannot predict the roll of a single dice, but it can model the behaviour of many rolls in terms of the possible statistical outcomes”* (Treut et al. 2007). It is this reasoning that provides climate scientists faith in their predictions about future trends in the Earth's climate. However, there is again resistance to the projections by the IPCC. The simulation models that are used to predict future climate are vast, both in their required computer power and their complex differential equations. In order to validate such models, a means of reproduction is needed and a form of checking. Those who support the complex predictions claim that those who disregard the predictions cannot reproduce the models or refute them, due to the large computers required, of which there are very few. One paper suggests, however, that there is plenty of evidence that simple forecasting models can add value to the complex models and a greater degree of model validation should be conducted in the climate science realm since it so far has not been robust (Fildes 2011). In essence, this is suggesting that while £50m computers running highly complex global

simulations increase the speed of the calculations required, if the parameters are not well understood, the projections may well still be wrong. These complex computer systems may be unduly inaccurate and simple forecasting techniques should be used alongside as a means of benchmarking. It should be acknowledged that these complex models have led to the decisions on legislation in Europe and have now set legally binding targets. Further argument draws on temperature data for the past decade, since IPCC predictions have covered this range. Figure 2.3 has been adapted from the AR4 IPCC report by Liljegren (2014) showing how predictions are not currently fully supported by recorded data.



**Figure 2.3:** Comparison of IPCC (AR4) surface temperature model projections (MM Mean SRES A1B data shows mean estimations of temperature increases and uncertainty range presented by dashed lines above and below) with actual 13 month Smoothed Observations from 2000 to 2/2014 (grey line for GISTemp and blue lines from satellite data) (Liljegren 2014b).

Figure 2.3 shows that the observed global surface temperatures from satellites have not followed predicted temperature increases during the start of this millennium. Fundamentally, the observed trend over the last 15 years has only been equivalent to

one-third to one-half of the trend over the last 60 years from 1951. This has increased debate on the validity of climate models in projecting into the future but it has never been the intention of the IPCC to predict near time frames. Even so, the IPCC reports in its most recent draft working paper of AR5 that such 15 year hiatuses in temperature are not uncommon in the larger temperature records and should simply be taken as proof of climate model failure (IPCC 2013b). While recent observed temperatures have not represented previous trends reported in earlier IPCC reports, even so they still seem to be within reported ranges by the IPCC, albeit rather lower than predicted.

An argument to explain this will again point to the fact that abrupt changes to surface temperature and perceived anomalies in short-term weather patterns are independent of the larger trends of the global climate. This evidence, however, can erode faith in legislation based upon climate science as laid out by the IPCC. Short-term climate events that are perceived as abnormal happen as seen recently with flooding in Cumbria, UK in 2009 (BBC 2009) and droughts and forest fires around Melbourne, Australia (BBC 2014) for example. They were first noted from the analysis of ice-cores and became known as Dansgaard-Oeschger events in the climatic system after the two scientists who were conducting the analysis on the ice-cores and flagged up these short-term changes in carbon dioxide intensities and global temperature fluctuations, to the order of a few degrees. In the historical context, these could not be assigned to human factors such as burning fossil fuels; they had to be a result of the natural cycle of the Earth. This could give strength to the argument that our current warm trend is part of the natural system and not due to human influences, supported study around the Medieval Climate Anomaly *or* Warm Medieval Period (Akasofu 2009; Soon & Baliunas 2003). It also, however, causes concern to those who would firmly agree with AGW as proposed by the IPCC since it is evident that abrupt changes in our climate can occur from relatively small forcing by changes in factors such as GHG concentrations since carbon dioxide levels have tended to correlate with temperature changes in the past (Treat et al. 2007). However, again by the IPCC's admission, there is "insignificant evidence to determine trends in small-scale weather events such as tornadoes, hail, lightning and dust-storms" (Barker 2007).

Governments have taken their conclusions from IPCC reports and not all have the same response to IPCC projections, highlighted by the lack of global agreement on the subject. This might lead to a requirement for a different premise by which to lead the

switching from unsustainable fossil fuels that currently the global economy depends upon. This message of leaving fossil fuel dependency behind could also act as a common agreement for the different viewpoints on projections and their relative meanings. The IPCC, and political consensus in some regions, has decided that the debate is no longer happening and moved onto concerted efforts to tackle AGW. Whether this is just or not, however, can be argued through the discussion of global production of fossil fuels that follows at the end of this chapter. The fundamental message resulting from viewing the climate, as a complex and delicate system that could react to human influences is that the system has finite resources and our global economy is still inseparable from fossil fuel use in order to supply the basic energy needs of a modern economy.

## **2.5 The Debate Shows No Signs of Cooling**

Warming of the Earth and Oceans has occurred in the past 130 years and is generally undisputed. The key questions regarding this current warming are: Is it not possible without GHG emissions increase and is it unlike the natural cyclical changes of the Earth's temperature? The most regularly used evidence against this is historic temperature time series that show the Medieval Climate Anomaly, from around 950-1250AD. It was presented after Mann's famous Hockey Stick Graph (Mann et al. 2009) and three years after the IPCC Third Assessment Report (TAR), that on review of 1000 year proxy records showing climatic and environmental history of the Earth, proxies were unfit to be used for full global temperature time series but were valuable indicators for local temperatures (Soon & Baliunas 2003). Soon et al. (2003) also went on to state that many of these proxy records showed that "*the 20th century is probably not the warmest, nor a uniquely extreme climatic period of the last millennium*". The Fourth IPCC report failed to argue this case after the removal of Mann's 'Hockey Stick Graph' and its lengthy and unpleasant critique. The most recent explanation of the warm "Medieval Climate Anomaly" by Mann et al. attempts to once again refute sceptics of AGW by stating that, although the Medieval Warm Period "matches or exceeds that of the past decade in some regions, [it] falls well below global recent temperatures" (Mann et al. 2009). As already mentioned in section 2.4, this also now appears in the latest IPCC assessment report (AR5) (IPCC 2013c). The paper's analysis is again on proxy records that are open to dispute. The debate has also been confused by fellow contributors to the IPCC report who state that, based on the "best proxy for Greenland temperatures", current temperatures felt in Greenland are not extreme in relation to the

Medieval Climate Anomaly, rather the period was “as warm or slightly warmer” than today’s temperatures (Vinther et al. 2010). Although these are localised temperature conditions, it has been stated by the IPCC themselves that the “warming signal” of AGW is amplified at higher latitudes. Most recently, more support has emerged for alternate explanations of AGW, presenting the possibility that temperature rises are part of different cycles to that of carbon dioxide – a gas that will release itself from liquid as temperatures increase – and that the observed temperature increases follow a longer, slower natural cycle since similar average temperature increases were felt by the Earth between 1800 and 1850, 100 years before carbon dioxide levels began to rise sharply (Akasofu 2013). It will be seen below that observed increases can be used by sceptics and supporters of AGW theory alike. This again leads to the requirement of a fresh debate concerning human-induced carbon dioxide levels.

While some reports sound ever more conclusive to AGW, there are still challenges to this theory since proxy data, described as “multiple spatially distributed proxy records” (Mann et al. 2009) has been used to create the evidence which, by the paper’s own admission, is still “insufficient” for estimating “spatially resolved large-scale temperature reconstructions beyond the past few centuries”. This is another example of how difficult climate science continues to be; both for the researchers who have been involved for decades and for those who wish to understand and plan from it. As sceptical views gain momentum, it is ever more dangerous for scientists to state, as above, the true uncertainty in their evidence for AGW. This could be part of the dilemma in the debate of global warming in that scientists have an inherent difficulty in expressing real uncertainty and accepting weaknesses in their arguments if a lack of real evidence can ever truly exist. This debate concerns timeframes beyond that of humans and concerns a system that is un-testable by laboratory means.

## **2.6 What does the Earth face from AGW?**

Under the assumptions of the concentration-driven IPCC scenarios, global mean surface temperatures for 2081–2100, relative to 1986–2005 will likely be in the 5 to 95% range of the models (CMIP5) which show global atmospheric-oceanic temperature outputs; 0.3°C to 4.8°C. The global temperatures averaged over the period 2081-2100 will increase by 1.8°C – 4.0°C relative to 1986-2005, the “best estimate” by the IPCC (Collins et al. 2013a). The AR4 figures span the range between low emissions scenario

and high emissions scenario. Within these, there is a possible range of increase of 1.1°C – 6.4°C, so called the “likely range” by the IPCC. It is said that these estimates rely on numerous “climate models of increasing complexity and realism, as well as new information regarding the nature of feedbacks from the carbon cycle”. It has already been discussed that these complex climate simulation models still do not persuade all parties and that inherent unknowns are still present. These feedbacks are important in the high scenario of temperature, with 1°C further warming by 2100 or indeed even exceed a 1.5°C increase (66-100% assessed likelihood) by the end of the century (Collins et al. 2013b). Much of the alarming statements regarding global climate projections obviously come from the high scenarios and thankfully, as yet are not proving to be accurate in the short-term.

Based on models by the IPCC, in order to stabilise carbon dioxide emissions at 450ppm - a threshold considered by the IPCC to be critical to avoiding irreversible temperature increases - would mean a reduction in the total emissions over the next century of 660 GtCO<sub>2</sub> (from 2460 to 1800 GtCO<sub>2</sub>). This sets a tangible target, although hard to discern. Emissions reduction targets are deduced from these large, average figures and follow at the end of this section. Mention of sectors, such as electricity generation, is specific to this thesis.

## **2.7 UK Projections**

The UK Climate Projections (UKCP09) by the Department for Environment Food and Rural Affairs (Defra) sums up the potential problem with projections, in that “*the extent to which human activities are contributing is still a matter of research*” (Defra 2009). However, for pragmatic reasons, there must be some prediction so as to plan for future temperature rises, whether it is from AGW or simply the Earth’s natural cycles.

Summer, winter and annual mean changes by the 2080s (relative to a 1961–1990 baseline) under the Medium emissions scenario are given below. Central estimates of change (those at the 50% probability level), followed in brackets by changes that are very likely to be exceeded, and very likely not to be exceeded (10 and 90% probability levels, respectively).

1. All areas of the UK warm, more so in summer than in winter. Changes in summer mean temperatures are greatest in parts of southern England (up to



4.2°C (2.2 to 6.8°C)) and least in the Scottish islands (just over 2.5°C (1.2 to 4.1°C)).

2. Mean daily maximum temperatures increase everywhere. Increases in the summer average are up to 5.4°C (2.2 to 9.5°C) in parts of southern England and 2.8°C (1 to 5°C) in parts of northern Britain. Increases in winter are 1.5°C (0.7 to 2.7°C) to 2.5°C (1.3 to 4.4°C) across the country.
3. Changes in the warmest day of summer range from +2.4°C (–2.4 to +6.8°C) to +4.8°C (+0.2 to +12.3°C), depending on location, but with no simple geographical pattern.
4. Mean daily minimum temperature increases on average in winter by about 2.1°C (0.6 to 3.7°C) to 3.5°C (1.5 to 5.9°C) depending on location. In summer it increases by 2.7°C (1.3 to 4.5°C) to 4.1°C (2.0 to 7.1°C), with the biggest increases in southern Britain and the smallest in northern Scotland.
5. Central estimates of annual precipitation amounts show very little change everywhere at the 50% probability level. Changes range from –16% in some places at the 10% probability level, to +14% in some places at the 90% probability level, with no simple pattern.
6. The biggest changes in precipitation in winter, increases up to +33% (+9 to +70%), are seen along the western side of the UK. Decreases of a few percent (–11 to +7%) are seen over parts of the Scottish highlands.
7. The biggest changes in precipitation in summer, down to about –40% (–65 to –6%), are seen in parts of the far south of England. Changes close to zero (–8 to +10%) are seen over parts of northern Scotland.

Defra show their understanding of the problem that arises from confusion in how accurate projections can be (Defra 2009):

*“To adapt effectively, planners and decision-makers need as much information as possible on how climate will evolve, and this has been the purpose of the successive publications of climate change scenarios for the UK”.*

It is an inherent need from humans for answers that has increased argument and division between all concerned parties of the AGW debate. Fundamentally, while Governments such as the EU have set policy around IPCC findings, there is still denial about the scale of AGW, rather than its existence. This has continuously prevented global agreement and it is highlighted by Helm (2012) that if the more expensive mitigation strategies are chosen now, such as wind power and carbon capture and sequestration technologies, there is likely to be greater resistance from both the public and decision-makers.

## **2.8 Peak Production Problems**

*“The production of a finite resource...starts when first tapped and ends in exhaustion, passing a peak in between.” (ASPO 2009)*

The following section briefly covers a number of studies into the likely peak production of oil, natural gas and coal in a global context. Peak production in this context refers to the maximum possible production rate of fossil fuels that can be achieved. This will be discussed in a global context in order to provide a general overview of the likely effects of reaching this maximum rate. Studies in this section have been chosen in order to suggest years in which peak production is likely to occur and that consider and discuss the wider context of production rates where political, economic and technological factors also play a critical role. While the effects of these factors on production are difficult to quantifiably estimate, a consideration of them acknowledges that peak year estimation is intended as a guideline. The uncertainty in their estimation is incomparable to that of future climate projections due to historical information on depletion of single resource amounts, whether they are from mines or fields. Also, unlike possible speculation into climate changes currently being observed and the likely causes, this section clearly presents recent and current effects of peaks in production being felt around the globe.

The concept of peak oil production was first discussed by M. King Hubbert in his revolutionary paper in 1949 in the journal, *Science* (Hubbert 1949). While it was known

that fossil fuels were finite, Hubbert suggested a method in which this finite natural resource could be modelled in order to predict the nature of growth and decline of the resource so as to better plan for its implications. Even in 1949, Hubbert commented that humans are managing a “*fixed storehouse of energy which [they] are drawing upon at a phenomenal rate*”. In modelling production rates of fossil fuels by a logistic curve, Hubbert was able to show quantifiably that a large rate of peak production would also result in a “*sooner and sharper*” rate of decline in that resource (Hubbert 1949). Hubbert was able to successfully predict the peak oil production that occurred in the US, although the use of his methodology tended to fail in predicting the peak in production globally and regions elsewhere, leading to criticism of his process and a period of disregard for such concepts as exhausting resources (Cavallo 2004). However, more recently, Hubbert’s concepts have begun to re-enter popular debate surrounding peaks of production due to a global awareness around problems with peak production.

The IPCC, and other organisations, have not adequately accounted for the reduction in production of oil and gas over the coming decades due to a peak in their global production; their scenarios and projections do not include insight from resource experts (Höök et al. 2010). Within the 40 scenarios that the IPCC offer for future emissions increases in AR4, there is “*exaggerated resource availability and unrealistic expectations on future production outputs from fossil fuels*” (Höök et al. 2010). Bizarrely, this results in projections over-estimating likely emissions due to the greater production of fossil fuels that will eventually be burned to emit carbon dioxide into the atmosphere; likely emissions will be less than perceived and hence potential AGW will be less. This highlights a lack of acceptance of the peak production debate even by those organisations that would stand to gain by the added focus from it.

As discussed, the argument about AGW has not ended, regardless of ever more ‘confident’ reporting by the IPCC, as per their own statistical scoring system. Due to its very nature, AGW may not be provable until it is too late to affect change, whether it is in humanity or nature. The issue, however, that continues to crop up is that whether Global Warming is happening or not, there will still be a problem with a shortage of resources. These same resources currently produce large volumes of GHGs and pollution. They are also finite. The BP Statistical Review (BP 2009) states that: “*The world has ample resources, with more than 40 years of proven oil reserves, 60 years of natural gas and 130 years of coal*”. This may be true on a basic level, for instance by

looking at the resources to production ratio in the published statistics. The globe has enjoyed an economic boom since discovering energy-rich fossil fuels, leading to the first half of the Age of Oil. However, as discussed by The Association for the Study of Peak Oil and Gas (ASPO), the second half of humanity’s Age of Oil will be “*characterized by economic contraction*” (ASPO 2009). As will be seen below, most commentators, including those directly involved in the oil industry, believe that the peak in global oil production occurred around 2008 and it “*is no coincidence*” that the recently felt global recession, that has been the most damaging in our economic history, “*coincides with this recognition*” (ASPO 2009). A report by the UK Industry Taskforce on Peak Oil and Energy Security (ITPOES 2010) agrees with this statement and shows the issues with production peaks in stark terms. A key message of the report is reducing the UK’s dependence on oil as quickly as possible in order to reduce exposure to “*volatile*” oil prices. The issue of peak production is perhaps far more important than simply stating the “*ample*” resources that are left.

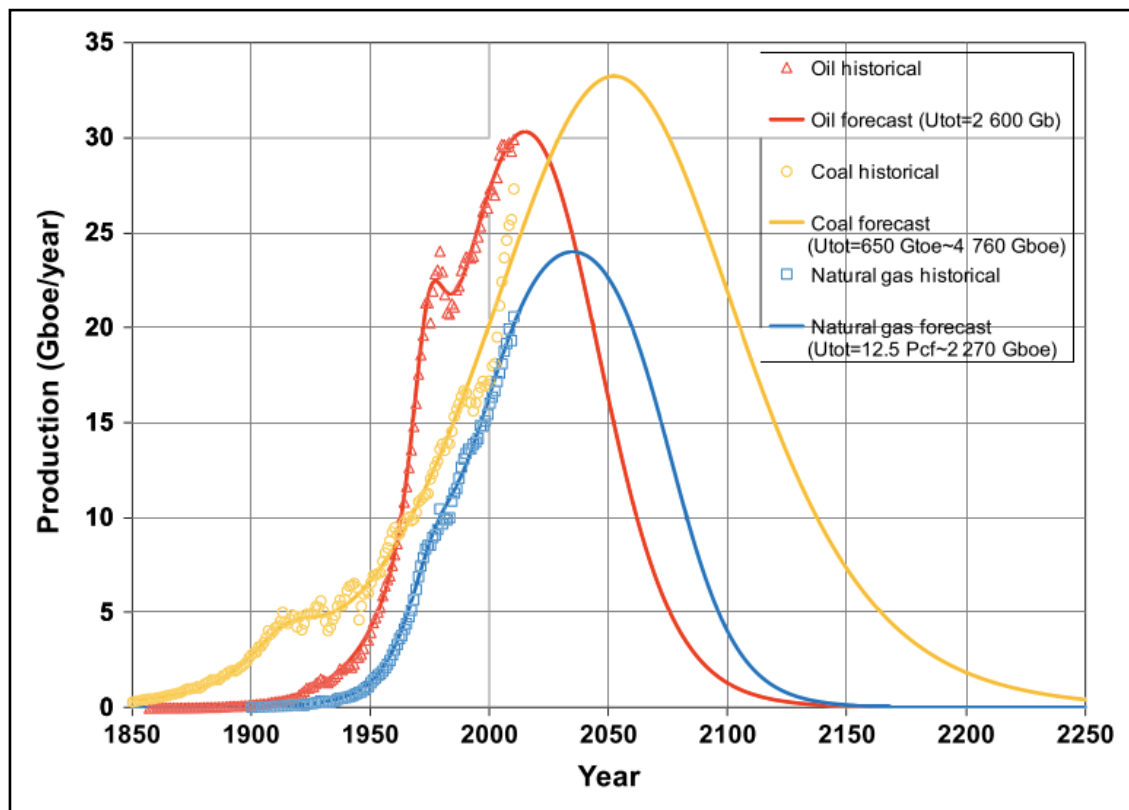
Table 2.1 and figure 2.4 suggest production profiles and peak years for global fossil fuel production, based on a multi-cyclic Hubbert approach by Maggio & Cacciola, (2012). It should be noted that this is one paper’s prediction and there are numerous other predictions from as early as 1956. A summary of different predictions exist in the literature (Hughes & Rudolph, 2011a; Tables 2,3) mainly focusing on oil and natural gas and acts to highlight how predictions have changed. Others will also be discussed in greater detail below.

<i>Fossil Fuel</i>	<i>Oil</i>	<i>Natural Gas</i>	<i>Coal</i>
<b>Year</b>	2015	2035	2052
<b>Production Rate (p/a)</b>	30Gb	132 Tcf	4.5 Gtoe

**Table 2.1:** Predicted global peak production years and rates for oil, natural gas and coal (Maggio & Cacciola 2012). *Units: Gb – Giga Barrels of oil, Tcf – Trillion Cubic Feet of Natural Gas, Gtoe – Giga Tonnes of Oil Equivalent of Coal.*

Key to the peak production debate is the forecasting of Ultimate Recoverable Reserves (URR). Firstly, there has been a rise in non-conventional sources of fuel such as Canada’s tar sands which have become viable due to economic conditions allowing these more expensive and more energy-intensive options to come online, but also technological advances such as hydraulic fracturing (fracking) to release shale gas have

changes the URR predictions globally and regionally. What is apparent, however, is that most of the newer technologies are energy intensive, costly (with the exception of fracking), and potentially polluting and are expected to do little more than delay a plateau or peak by more than a few years, according to Hughes & Rudolph (2011a). This highlights also that production of fuels is intrinsically linked to the global economy and factors other than technological advancements and URR levels will affect the ability to obtain these finite resources.



**Figure 2.4:** Fossil Fuel Production profiles (Maggio & Cacciola, 2012; Figure 16)

It should be mentioned that the largest body who report on this, the International Energy Agency (IEA), have not tended to agree with the concept of nearing peak oil production, and suggest oil demand peaks at around 2035 at nearly 100 million barrels per day (Mb/d) (IEA 2012). No peak in supply is mentioned. However, the IEA have been guilty of changing from a positive perspective to a negative one and back again, making it difficult for decision-makers (Miller 2011). Other issues with the IEA's projections have been reported on in that they tend to over-estimate oil supplies and appear too optimistic in all of their recent forecasts; in particular projections to 2035 are deemed overstated by some since the peak production of crude oil has likely been reached (Alekklett et al. 2010). This sentiment is also echoed by other authors, claiming that the

reference scenario in the IEA's World Energy Outlook seems *"inconsistent with historical depletion rates and seems to rely upon optimistic assumptions about future decline rates"* (Sorrell et al. 2012) and with regards to oil reserve data that is available in the public domain, it can tend to be *"contradictory in nature and should be interpreted with caution"* (Owen et al. 2010).

While some will refute Hubbert Peaks of production and indeed the years at which they occur due to the inherent nature of fossil fuel production being linked to technological, economic and political constraints (Cavallo 2004), it should also be noted that many within the oil industry now agree with a range of 2009 - 2021. The CEO of Total, Christophe de Margerie, has been quoted saying *"the capacity that the oil industry has to go to 93-95m barrels per day is already over. There will be a shortage of energy in the medium to long term."* He also mentioned that he saw 89m barrels a day as the realistic maximum production rate, coincidentally in 2008 (Chen et al. 2009) which can also be seen from Figure 2.4 that this was not altogether wrong. It is also shown that while the social constraints could affect these peaks, production rates are quantifiably linked to reserves-to-production ratios, the rate of production growth and the degree of reserve replenishment during a year, according to Feygin (2002). In essence, this clarifies that quantifiable estimates can be made in order to obtain reasonable peak year scenarios. Almost all oil products used by societies are made from non-renewable sources. While the ultimate recoverable resource (URR) is being added to by newer and more complex technological advances such as hydraulic fracturing, tar-sands extraction technologies, Arctic exploration and other novel reserves and non-conventional production methods, these are nearly all more expensive, more energy intensive and potentially far more polluting and are expected to do little more than delay a plateau or peak for more than a few years (Hughes & Rudolph 2011a; Miller 2011). Helm (2012) however would argue that these unconventional sources are so plentiful, that they will become conventional in that they are widely abundant. In the case of fracking also, it has not followed that unconventional sources of gas are most expensive, with US fracking resulting in a wholesale price of gas at its lowest at one-fifth that of in Europe (Helm 2012).

It should also be mentioned with regards to the coal estimate that while there is a range of possible years under different scenarios from 2010 and 2048 (Mohr & Evans 2009), separate estimates are similar, such as 2030 by the Energy Watch Group (EWG), based

on an in-depth study of each region that produces coal globally (Höök et al. 2008). Figure 15 in this report also offers a global production profile, similar to that of Figure 2.4. Both mentioned reports also call into question the reserve estimates that are given for coal with extensive downgrading (reduction in the total amount) of coal reserve figures (Zittel & Schindler 2007) being more common than upgrading (increase in the total amount) of coal reserves. This leads to a reduction in the risks that may occur from peak production (Cavallo 2004).

Whether global peaks have now passed or are approaching seems to be less important than an acknowledgement that they will soon be impacting on the global economy. Commentators from mainstream circles are now warning of the threats of being in an ever-declining environment of oil, gas and in the future coal. Exports may well not be able to meet demand in Europe and the UK within 10 years according to some (Fells & Whitmill 2008). Global competition is also mentioned as critical for obtaining access to fossil fuel supplies. Whether or not these peaks in production rates are close, societies should be able to cope in a scenario of less oil (Hughes & Rudolph 2011b). One commentator (Friedrichs 2010) takes historical cases of resource shortages, limiting conjectures to a few decades post event, in order to suggest a number of scenarios that could result from a reduction in available resources such as predatory militarism (as seen in Japan prior to their entering The Pacific War), totalitarian retrenchment (the elite members of society were favoured over the poor in North Korea) and socioeconomic adaptation (Cuba's oil embargoes leading the regime to encourage non energy-intensive methods of food production). Whatever the scenario, it seems entirely reasonable that different regions will react very differently with huge unknowns and not without social unrest.

The recent economic crisis has given weight to previously theoretical comments that as peak production rates approach, fuel prices and price uncertainties increase severely and *“the economic, social, and political costs will be unprecedented”* (Hirsch et al. 2005). Oil and gas contribute to almost every product and service in the global economies and therefore the ramifications are very large. This is a far cry from the still disputed debate on climate projections while still fundamentally driving similar change. Fossil fuel production rates are also likely to continue or plateau around a theoretical peak, thereby increasing the rate of decline of the resources exponentially. Without a concerted effort to remove dependence, the implications are ultimately bleak.

Due to the legislation and awareness of global climate changes, carbon dioxide has become a commodity by which a new market has been constructed. However, it should be seen from this chapter that what is crucial is the consumption of carbon that leads to the emission of carbon dioxide and the emissions themselves. As suggested by Hopkins (2008), climate change could be seen as concerning the emissions from a car while peak production concerns the fuel entering the car. More simply, if we tackle the fuel going into the car, the emissions will be reduced as a result. The emissions issue should not necessarily drive the policy on changing the fuel. Policies must also ensure a reduction in GHG emissions while maintaining secure supplies of energy. Due to the volatility in global and regional energy markets, the availability and affordability of fossil fuels can directly affect a region's energy security and its climate policy:

*“Preparing for peak oil and ensuring the energy services currently supported by oil products will need to accommodate both energy security and climate change challenges; solutions that are environmentally sustainable and able to maintain a reliable and affordable supply of energy services.”* (Hughes & Rudolph 2011a)

As has been mentioned in this section and will be discussed further in following sections, it has not necessarily been the case that carbon mitigation reduces primary consumption as for example in the case of carbon capture and storage technologies for thermal power plants. It is this key message of ensuring energy-intensive consumption is reduced that this section outlines. The following section outlines the legislation in place in the EU that has come from fears over climate change and reliance on non-renewable fuels.

## **2.9 How Have Governments Responded?**

Climate change is a continuous issue for the human race. Whether it is our fault or not, there will be climatic events such as storms, floods and droughts. However, for policy makers, it has become more extensively discussed than the issues that relate to it, such as the peak in production rates of resources. Observed GHG increases in the atmosphere have come from the exponential growth of fossil fuel use in society. Guarding critical infrastructure from vulnerability due to lack of resources is likely to be just as key as climate change itself. Ensuring a sustainable approach to electricity supply, for instance,



means developing electricity generation methods that will run on less, or ideally no, fuels that cannot be sustained at an acceptable level to the country or region that they supply. This time in history is the first in which resources are becoming volatile in relation to their supply and cost, not on a regional level, but on a global one. Sustainability is to become a critical factor for businesses, potentially through policy and strict regulation, but also through necessity.

*“The negative effect of oil price on the macro-economy is significant, and should be used to build the business case to invest in alternative energy carriers. Many alternative fuel carriers also present the double dividend of improving energy security (i.e. utilize local resources) and reducing emissions (i.e. electricity, hydrogen).”* (Owen et al. 2010)

The EU’s response to the stark warnings from the IPCC and others was the EU’s Renewable Directive. The 2008 Climate and Energy Package was the part of this that set the binding legislation to ensure the EU hit its ambitious targets. These targets, known as the “20-20-20” targets, are:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency.

For member countries, these targets could mean slightly different levels and the UK was given the target of a 15% renewable energy target, since its starting point of renewable energy capacity was lower than any other EU member state except for Cyprus and Malta (Helm 2012). This target should be seen as energy produced by renewable technologies, in other words, not simply installed capacity but how much renewables contribute to demand. It has been seen that the total wind energy share of EU energy consumption in 2011 was 7.8% (7.1% by onshore and 0.7% offshore) (EWEA 2014). This figure can be compared to wind energy’s share of total installed capacity for the same period (2011) of 10.5% (EIA 2014).

The Renewable Directive sets the EU Emissions Trading Scheme (EU ETS), which created a paradoxical side effect as discussed by Helm (2012). Due to the increase in renewables and their forcing onto the systems of member states by policy measures, the

carbon price in the EU ETS has the potential to fall. This will increase the competitiveness of coal and gas, which consequently increases their share of electricity generation, so that the potential exists that the resulting emissions reductions are lower and at the limit completely offset. In reality the EU ETS dramatically failed in its first phase to create a high price for carbon that would effect this switch from fossil fuels and indeed the relative price of coal to gas had more of an effect on technology choice in the UK (Defra 2008). UBS Investment Research indicated to clients that the EU ETS system had cost \$287 billion up to 2011 with “*almost zero impact*” on overall emissions in the EU and this amount of money could have resulted in approximately 43% reduction in overall emissions if it had been used in a targeted way such as upgrading power stations (Mahar 2011).

For the UK, the aligning legislation for the EU Renewables Directive is the Climate Change Act 2008, which introduced a legally binding target to reduce GHG emissions by at least 80% below the 1990 baseline in 2050, with an interim target to reduce emissions by at least 34% in 2020. The Act also introduced ‘carbon budgets’, which set the trajectory to ensure the targets in the Act are met (CCA 2008). This put direct pressure on the ability of Government to effectively account for GHG emissions.

It is recommended by this chapter that the UK government should:

1. Reduce the emphasis on climate change projections and threats that still contain a degree of uncertainty that is not measurable.
2. Utilise technologies that are not only focussed on produced GHG emissions but are not unreasonably expensive during their whole life cycles.
3. Discuss peak oil and the associated risks in greater depth.
4. Move to a standard GHG emissions accounting practise that monitors consumption-based carbon emissions immediately. This will be discussed in detail in Chapter 4 of this thesis.

The nature of the debates within the climate science arena has left those who decide on policy and academics with a confused picture and one that has increased resistance to definitive action. Clearly, this is not in the best interests of decision-makers and has led to a perhaps rushed attempt at persuasion by scientists involved. A reduction in fossil fuel requirements throughout the global economy could only lead to a long-term security that is in doubt at present. There has been little or no common ground since

both parties are concerned with a confirmation of their views rather than finding some middle ground for discussion and an acceptance of more real, short-term goals that could ultimately reward all parties. The very real threat of peak fossil fuel production gives an opportunity for all parties to discuss the raised issues in a much more diverse way than the AGW debate alone has done so far. The current EU legislations that have shaped UK legislation are focussed on the production of emissions. Based on the evidence presented in this chapter, it is unwise to only consider these emissions without also including the consumption of carbon-rich products. The best course of action for the UK is one of whole life cycle thinking of available technologies in order to understand and reduce the resource costs of energy projects in relation to this thesis. This is since electricity and its associated resource costs feeds into every aspect of the UK economy.

Chapter 2 will present the current state of the UK electricity supply network and discuss how robust the infrastructure is for coping with the transition to renewable technologies.

### Chapter 3 - The UK Energy Sector

This chapter outlines the UK's current electricity generation situation as well as the short to medium term goals of the UK Government to improve electricity generation in key areas. This focuses on electricity supply and the UK Government targets for a diverse mix of supply capacities while reducing overall associated GHG emissions. Without a secure energy future, there will be less economic ability to afford to reduce fossil fuel use, and in turn GHG emissions.

A reduction in electricity demand will inevitably play a role in the targets set out by the UK Government and European Union, and could prove highly influential in ensuring a sustainable electricity market. However, this may also be offset by electricity demand increases from new technologies such as heat pumps and electric vehicles as seen in the "Gone Green" and "Accelerated growth" scenarios set out by National Grid (National Grid 2012b). The emissions reduction that is provided by a demand-side intervention in the electricity system is typically assessed by means of an assumed grid emissions rate. This "marginal emissions factor" represents an emission rate of the GHG intensity of electricity **not** used as a result of the change to the system and understanding this rate provides insight for policy decisions into reducing the overall GHG emissions intensity of electricity (Hawkes 2010). The technical implications of changes in demand can be discussed in terms of UK supply efficiency and UK capacity margins, but this chapter does not attempt to provide insight into how to affect demand since this thesis concerns itself with total life cycle GHG emissions from supplied electricity.

The UK has not succeeded so far in effectively reducing fossil fuel use in its electricity supply sector. Figures from the Department of Energy and Climate Change (DECC) showed that the tonnes of carbon dioxide per GWh electricity supplied from fossil fuels increased between 2010 and 2012. Per GWh electricity supplied from all fuels (including renewables and nuclear), there was an increase of 26 tonnes of carbon dioxide per GWh electricity supplied (DECC, 2013; Table 5.C). Within the EU, the UK was third lowest in the EU standings for installed capacity of renewable plant types, at around 5.5% in 2009 (without pumped storage included) (DECC, 2009b); only Luxembourg and Malta had lower percentage shares of installed renewable capacity (Fells & Whitmill 2008). The latest figures, as published by DECC, show the share of renewables to total electricity generation in the UK as 11.3% in 2012 (DECC, 2013;

Chart 5.2). At the time of writing the UK is second only to Germany in the EU in relation to share of renewables to total electricity generation (RWE 2013a). The installed capacity of wind power alone, the largest renewables technology contributor in the UK, stands at 10.8GW (RenewableUK 2014). Even though a reduction in emissions has been seen, this mainly seems due to exchanging coal generation capacities for gas over the past decade (DECC, 2009a; Annex E). Something has held the UK back in decisions on other forms of new capacity. The lack of development in the energy sector has been in contrast to political will - apparent in legislation and funding incentives for new electricity projects through the Renewable Obligation Certificate Scheme (ROCS). The following chapter discusses the decisions required for the next 15-20 years and highlights how important it will be to put in place an assessment methodology for a range of different power plant types.

There are four factors that the UK Government has set out as driving policy and change in the energy markets in order to move to a low carbon economy (DECC 2009b):

1. Cutting emissions;
2. Maintaining secure energy supplies;
3. Maximising economic opportunities;
4. And protecting the vulnerable.

As seen in Chapter 2, disputes over emissions' importance and an over-emphasis on greenhouse gases could be causing confusion in sectors, such as the energy sector. Beginning such a list with emissions reductions suggests that decisions have suffered from an over-emphasis on areas of electricity projects that would improve as a consequence of the other key drivers such as energy security, resource depletion and trying to reduce fuel poverty. These are inextricably linked to fossil fuel dependence, regardless of the likely implication that carbon emissions are adversely affecting the Earth's climate systems.

### **3.1 The Electricity Supply Situation**

The UK has an ageing fleet of power stations. Important decisions are now being made on future electricity generation that will meet both the legally binding requirements, and technologically critical goals. In relation to electricity generation, 30% of electricity

demand will need to be delivered by renewables by 2020 while providing a reliable, secure electricity supply.

UK and global dependence on fossil fuels for supplying energy and specifically here, electricity, has led to a potential fuel “crunch” (discussed in Chapter 2) and problems associated with the global peak production of finite resources. Regardless of the legal requirements to reduce emissions, it is critical for the first goal of providing a reliable, secure electricity supply. However, it is also clear that some new technologies are not yet able to provide the security of supply that we demand – indeed technologies such as carbon capture and sequestration (CCS) could lead to the erosion of security of supplies even more by creating a further increase in fuel consumption of up to 37% (Owens et al. 2010). The Institute of Civil Engineers puts the UK’s position in plain words:

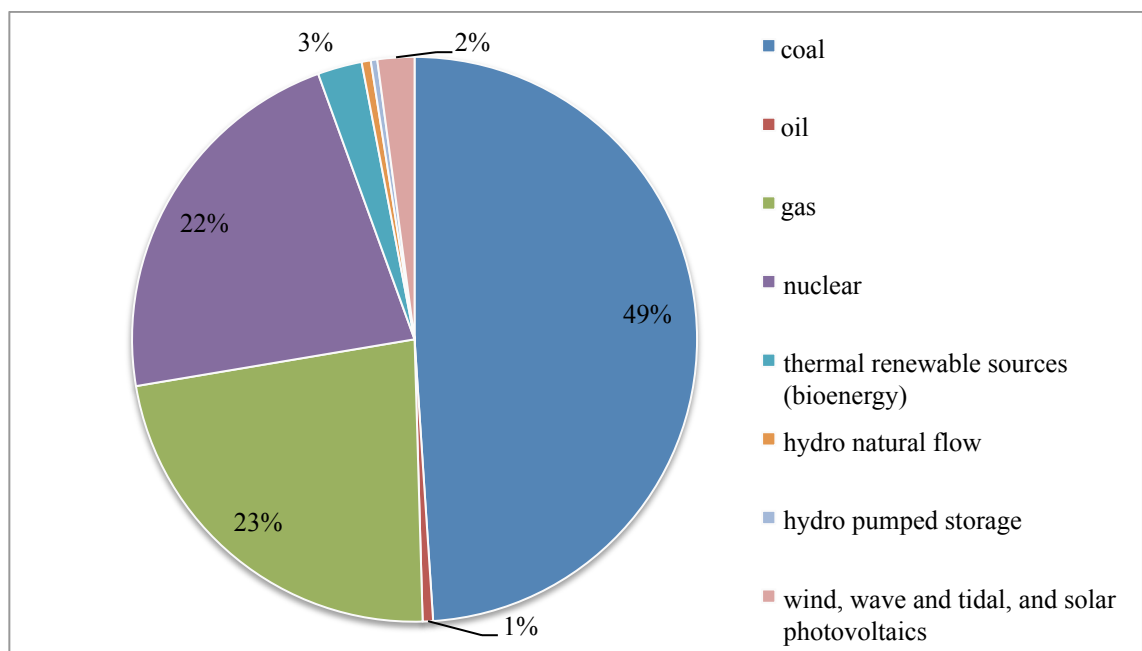
*“Changing the electricity generation mix is leading to a potential erosion of systems flexibility, exposing the UK electricity supply to risk of blackouts.”* (ICE 2009)

This is not simply referring to the move to intermittent renewable power plant types that will be discussed in this chapter, but also the lack of decisions on traditional power plant types and a significant and worrying potential energy shortfall within the next 10 years. Ofgem whose main function is to protect the interests of existing and future customers, show a situation of critical generating capacity margins especially in 2015/16 that erode security of supply (Ofgem 2012).

The UK Government currently promotes a range of electricity generation technologies, in order to provide the recommended diversity of supply: coal and gas fired power stations, with the intention of deploying or retrofitting CCS technology; nuclear power and renewables with onshore and offshore wind currently the chosen options available on a large, commercial scale. Hydroelectric power plays a role in UK generation capacity, but has little ability to increase its supply capacity and currently acts as a primary storage capacity (DECC 2013). There are other renewable options proposed, such as biomass, which can also be co-fired with traditional fuels such as coal in traditional thermal plant but questions have been raised over land requirements for growing the biomass in a sustainable manner in order to meet the demand for food, timber *and* bio-energy (Weighell 2011). Around one third of biomass flowing through

the UK economy is also currently imported (Weighell 2011) and this carries a significant amount of embedded GHGs. Wave and tidal resources in the UK are also significant, but are not yet at commercial scale as of 2014. These have potential equivalent to wind resources and should be seen as an important part of the future electricity mix in the UK. However, wave technology remains far from commercially viable despite considerable efforts since the 1980s due to its significantly higher costs when compared to other generation technologies (SI Ocean 2013) and has meant that growth in this sector is still behind other forms of renewable technologies.

The following figures (Figures 3.1 – 3.3) use the most recent data published in the Digest of United Kingdom Energy Statistics 2013 (DECC 2013).



**Figure 3.1:** Electricity Fuel Use in 2012. Those segments not labelled are below 1% (DECC 2013)

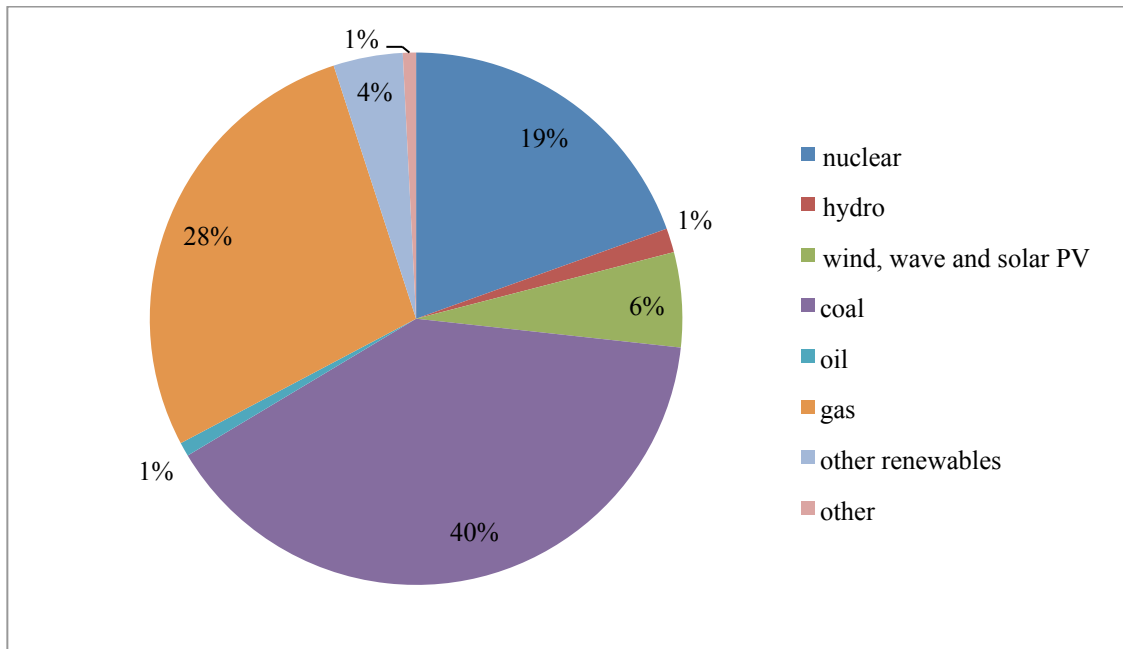
Figure 3.1 shows that over 70% of primary energy for electricity generation are dependent on fossil fuels and in particular, coal for electricity generation. For electricity production by technology, see Figure 3.2. Gas was favoured since coal prices rose significantly more than gas prices in 2008, resulting in a trend to switch to gas power stations. Indeed, 2008 saw the highest recorded use of gas (16% more than 2007, while coal usage dropped by 8.2%). This was also compounded by the fact that nuclear power stations generated 17% less electricity due to outages, repairs and maintenance (DECC 2009b). However, since gas prices are heavily influenced by oil prices, they have

recently become more expensive than coal, resulting in a significant increase in the use of coal in the UK from 2011 with gas power's share of electricity generation reducing from 40 to 28% and coal power increasing from 30 to 38% (DECC, 2013; Chart 5.2).

The UK is in a difficult position of either reacting to legislation requiring the deployment of coal power stations with CCS and suffering further price fluctuations, or relying on gas supplies that are more susceptible to price fluctuations. Gas has a greater price uncertainty attached to it, and as shown in the previous chapter, global, and indeed regional gas supply will likely peak earlier than that of coal. The more recent expansion of fracking in European countries, however, may provide similar price reductions as seen in the US of up to 80% and some claim US gas may even fill a significant portion of European gas demand (Friedman 2014). This may only realistically happen towards the end of this decade however even in an optimistic scenario (Baker 2014). While UK PM David Cameron has said fracking will help reduce domestic energy bills, more recent reports and comments from Lord Browne, CEO of Quadrilla, the largest fracking company operating in the UK, have suggested this is unfounded in a European energy market (Carrington 2013). More recently, the UK Government has had to reverse its statements on the potential of fracking to reduce energy bills (BBC News 2014). While these articles should be taken in relation to the authors and journalistic opinion, it highlights further unknowns and a continued exposure to fossil fuel market fluctuations. It could be argued that carbon economic metrics have clearly failed to reduce the fluctuations in price of fuels that effect changes from gas to coal and vice versa.

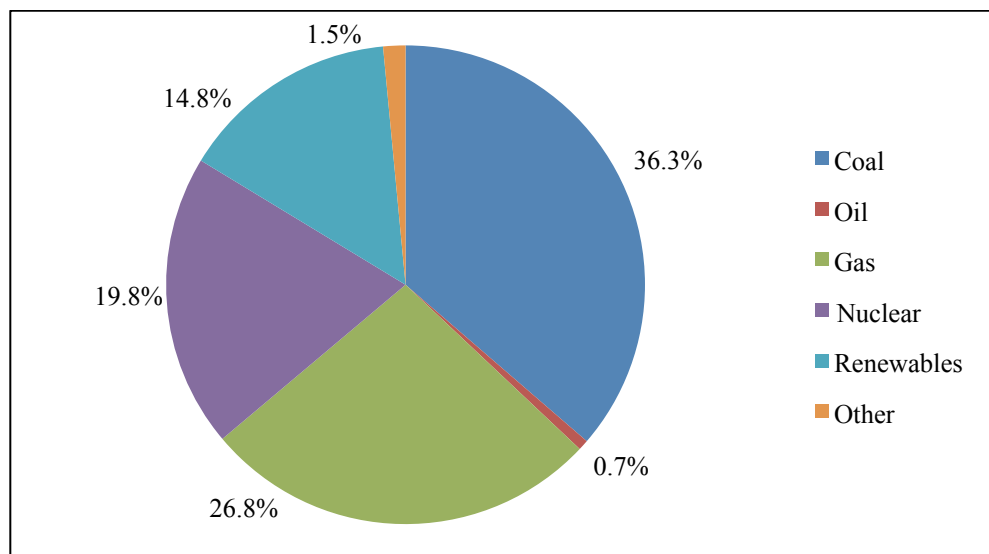
The UK is a net importer of fuel and of electricity, of which 3.7% of the total electricity supplied is imported. Of the 96% of the electricity generated domestically, figure 3.2 represents each technology's share of the electricity produced.





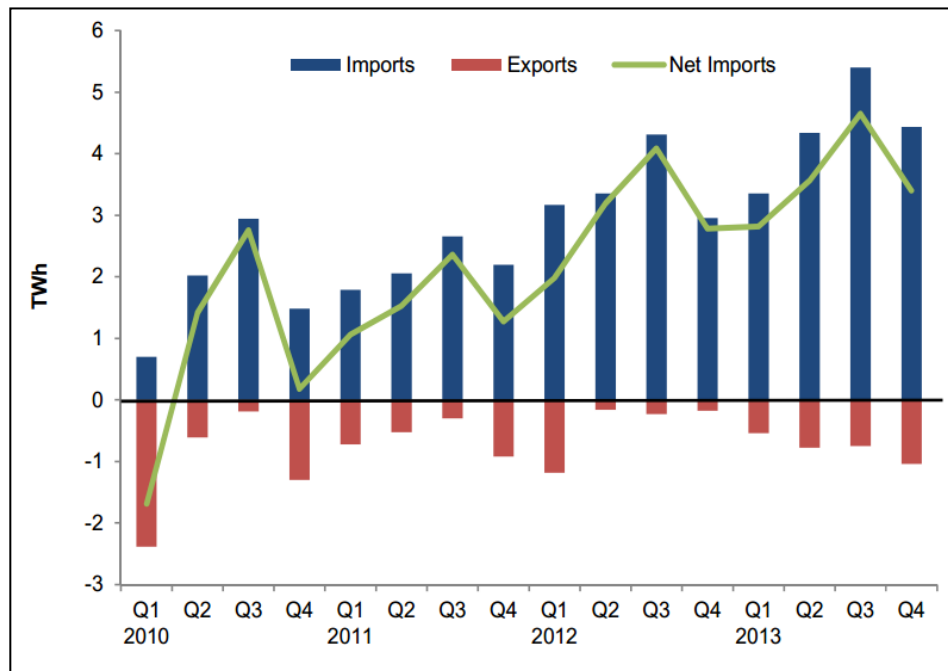
**Figure 3.2:** Production of Electricity in 2012 (GWh). Categories as used by DECC (2013; Chapter 6)

Figure 3.3 is needed in order to finally attribute this electricity production to generating capacity of UK power plant types. This phrase is preferred due to the traditional term “power stations” being less appropriate now that renewable energy installations, mainly wind farms and hydroelectric plants, provide a percentage of generating capacity.



**Figure 3.3:** Total Electricity Generation in 2013 by technology type (DECC 2014)  
 Baseload capacity has come from nuclear power predominantly, but also fossil fuel power stations have been critical to supplying UK electricity demand. There are also

remaining issues with the UK's requirement to import electricity with a continued upward trend of this as seen in Figure 3.4.



**Figure 3.4:** UK trade in Electricity (DECC 2014)

Fundamentally, there are big decisions to make on new generation capacity since a large amount of the UK's capacity in the electricity network is scheduled to change rapidly in the coming years, further compounding the issue of import dependence (Ofgem 2012).

### 3.2 Changes to UK Capacity

The UK requires commissioning of more than 20GW of new capacity by 2020. This represents around 22% of total installed capacity. However, it is not simply closures of existing plant that are important, but that the electricity network will contain more intermittent generation such as wind, and possibly wave generation, as well as more inflexible generation such as nuclear (DECC 2011a). This increases the challenge faced by National Grid in meeting demand at all times. Ofgem (2012a) clearly show that 2015 and 2016 are critical years, during which there will be a low capacity margin, the level by which available electricity generation capacity exceeds the maximum expected level of demand.

Figure 3.5 shows a scenario generated from the following key information from the UK Government and Sector bodies with regards to capacity changes over the next decade. Peak Demand is taken from National Grid's base case of 58GW that will not significantly change over the next decade notwithstanding significant new technology deployment. The other sources of information for individual technologies are shown below.

### **Coal, oil and mixed**

The oldest operating UK coal power stations are 47 years old, of which there are three, one of which closed this year due to a fire (DECC 2013). The youngest is 32 years old. Six new power plants are planned and all will likely require CCS if they are to open in the UK (DECC 2012a). Significant closures totalling 12GW of coal-fired plant is scheduled by 2016 due to the Large Combustion Plant Directive (LCPD).

### **Nuclear**

Only two nuclear plant type will be in operation by the end of this scenario since 16 reactors are to be retired by 2023 and one new plant (Hinkley C) will come online in 2023 and after a number of plants will have their operational lives extended (World Nuclear Association 2013). A further 16GW of new nuclear power capacity at eight sites around the UK is planned but it is not yet guaranteed to be online before 2023 (Nuclear AMRC 2014).

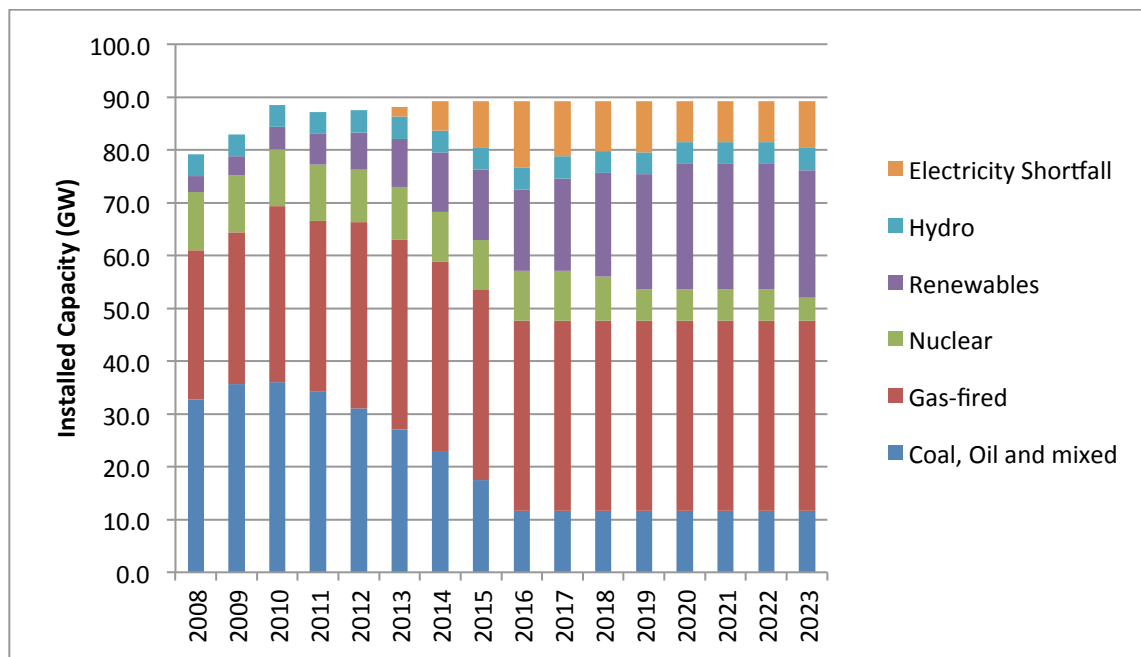
### **Gas**

Gas power is significant in that it is the most suitable plant technology for reacting with intermittent sources of generation due to its short start-up times, when compared to coal and nuclear plants. However, as has been mentioned, it is also subject to price uncertainty. It is likely that the depicted shortfall from the above scenario will be taken up predominantly by gas-fired power for these reasons as well as the relatively short times to build new plant. It is also seen in 2008-12 that this technology was the main contributor to increased capacity.

### **Renewables**

18.2GW of wind farms were under construction, consented or in planning as of 2013 (DECC 2012c) but assuming consents relative to historic figures, 2.7GW may not be continued. The total capacity required is equal to 23.47GW - 30% of total generating

capacity - in 2020, based on the presented scenario's calculation. After 2020, renewables contributions will remain at 30% of the electricity generated in this scenario. Tidal resources could supply in excess of 10% of total UK electricity (Sustainable Development Commission 2007) while wave resources are considerably greater, estimated at 50TWh/year – enough to meet around 14% of UK electricity demand (RenewableUK 2010). This however, in a pragmatic sense, is still speculation and as mentioned, wave and tidal projects have not been demonstrated on a commercial scale and in order to be conservative in this scenario no specific capacity is considered other than what could be assumed that would contribute to total renewables, meeting the 2020 EU targets.



**Figure 3.5:** Changes to UK Capacities over the next decade. (2008-12 from published data (DECC 2013) and 2012-23 taken using the assumptions detailed in the text, including meeting EU targets for installed renewables)

It is important to realise that renewables will be unable to meet 2020 targets without adding approximately 2.1GW per year. There have been contrasting global projections for annual capacity increases of wind capacity. The International Energy Agency (IEA) suggest as little as 5% annually (although up from 2.2% in 2008 projections) in their reference scenario (IEA 2009; Figure 9.2), while the Energy Watch Group (EWG) suggested 30% was more realistic (Rechsteiner 2008). This is a large range and is difficult to relate to UK wind capacity increases. This scenario increases wind capacity linearly at 2.1.GW per annum based on meeting our renewable targets. A review of

projects either under construction, consented or in planning, suggests Figure 3.5 is not unreasonable. Chapter 5 will also show how growth in wind power within the EU has exceeded most projections to date. Based on these figures, UK targets appear achievable. Optimists believe strongly that “*wind power generation will be the same volume as conventional plant types as soon as 2025 if historical growth of wind sector continues or construction of nuclear and coal plant types come to an end and natural gas plant types are used for peak demand only*” (Peter & Lehmann 2008). There were other suggestions for the likely build rate of wind power in the UK, expressed by Parsons Brinckerhoff who suggested a capacity build rate of 800MW per year (Parsons Brinckerhoff, 2009; Table 9.5.2). This estimation comes from wind farms installed in the UK in 2008, therefore it is based on real figures, but it is also now a historical figure and is below the annual increases now seen in the UK (DECC 2013). It is the legally binding EU targets that will drive the required increase through subsidy and political support. This is why it is assumed that 2.1GW is feasible. This compares similarly to the build rate of combined cycle gasification turbine power plant during the ‘dash for gas’ during the 1990s (Parsons Brinckerhoff 2009) with a lead-in time of 4 years as opposed to wind power’s 3 years, favouring wind.

### **3.3 The Shortfall**

The Government is optimistic in suggesting that a shortfall in generation will not occur in UK electricity supply:

*“There is significant new generating capacity under construction or in planning and the Department of Energy and Climate Change (DECC) projects that it is sufficient to exceed peak demand through the next decade”.* (DECC 2009b)

The scenario presented in this chapter concludes that new developments can meet renewable targets but extra capacity will have to be installed by 2016. More so, coal became the fuel most used in power generation during 2012 and 45 million tonnes of coal was imported in 2012, only 11% lower than the record high in 2006 (DECC 2013). Indeed, it has been stated that all Governmental projections suggest “*a significant reliance on imports*” as supported by Figure 3.4. Around half of the UK gas import requirements came from Norway last year and nearly half of all coal imports came from Russia, with Columbia and the US predominantly supplying the rest (DECC 2013).

DECC suggests that “*given the abundance of coal reserves, availability is unlikely to limit the future use*”. However, based on the previous discussion of peaks in production of fossil fuels, this could be a dangerous opinion and while fracking may provide considerable gas supply locally, it may not have the desired effect of reducing import needs and reducing the cost of natural gas within the EU. The array of international and environmental risks affecting future prices of these fuels leads to greater uncertainty around them for investors and policy-makers alike and could erode our energy security as effectively as a switch in our electricity generation technologies, if they are not properly accounted for. Indeed, some believe that ignoring the price of fuels and their associated price uncertainties, while only focussing on the costs of electricity generation, will result in only half the picture of technology effectiveness being made clear to policy-makers (UKERC 2007). This is discussed further in section 3.5 of this chapter. There has also been considerable uncertainty of the UK energy markets prior to the release of the Electricity Market Reform (EMR), where the first capacity auction took place in December 2014 and was perhaps one of the most important legislation mechanisms in terms of planning for electricity capacity. This is also combined with uncertainty over the carbon price floor and the lack of a holistic energy system strategy to create uncertainty that does not offer a good environment for tackling the current situation in the UK (Royal Academy of Engineering 2013b).

The traditional view is that international import requirements are still more secure than renewables even though renewables are now beginning to supply substantial capacities in Europe (RWE 2013b). DECC argued that the Russia/Ukraine gas disputes showed that reliance on imports “*highlighted risks associated with imported supplies*” while also suggesting that the UK was sheltered from this particular event and so the UK still held a strong position (DECC 2009b). It still suggests, however, that there are clear uncertainties in import reliance. It could therefore surely be argued that in the long-term goals of a country, import reduction should be a critical factor. DECC has previously projected that the UK’s own natural gas production will halve by 2020 (64bcm to 34bcm). This however may now change if fracking is commercially developed in the UK. In the short term, gas import dependency was to “*increase to 2014 then begin to level off as a result of reduced demand*”. This reduced demand was presumably based on meeting EU reduction targets; the only large event to reduce demand in recent years has been the economic recession in 2008-09. The reduction will also be affected by an increase in domestic electricity production from wind farms and other renewable

technologies. However, it is important to note that gas-fired plant will be of great importance to security of supply in a system containing intermittent sources of electricity, such as wind power. This will be discussed in further detail in Chapter 7. In 2013, renewables contributed to 14.8% of total electricity generation (Figure 3.3) and so their continued growth will help reduce import demand, provided there is a corresponding fall in fossil fuel use (especially high-carbon fossil fuels such as coal) which as has been mentioned does not yet appear to be happening. As seen in the previous chapter, technologies such as CCS being utilised on thermal plant to reduce GHG emissions will likely increase fuel consumption significantly, adversely affecting import dependency. It has been seen in the recent global economic recession that predicting GDP is important to future security of supply characteristics since it is strongly correlated with electricity demand. This creates a dilemma for policy-makers since economic recovery is crucial, while also jeopardising demand reduction targets.

The adequacy of gas supplies on cold days or during a cold spell is an important indicator of security of supply. While National Grid boasts figures such as 99.99974% reliability of supply and 94.55% system availability (National Grid 2009), during the winter of 2010 the UK imported electricity significantly, with the largest figure for imported electricity on the 1<sup>st</sup> January 2010 at 1.99GW (National Grid 2010). The total gross system demand at the same time was 45GW; therefore, around 4.4% of this demand was met by imported electricity from France that produces around 80% of its electricity from nuclear plant (European Commission 2012). Some suggest that there appears to be a “declining trajectory” of available traditional thermal plant capacity through to 2019 (Royal Academy of Engineering 2013a). Generation diversity and de-rated capacity margin relative to peak demands are examples of key indicators of how a secure UK the electricity supply network is and this will be elaborated on below.

Figure 3.5 has shown that under the presented scenario this ratio of installed capacity to peak demand (capacity margin) will steadily decrease over the next decade, notwithstanding significant investment and changes to current installed generation capacity. This is a consequence of changes in capacities of the various power generation technologies. It also does not tell the full picture. De-rated capacity is an alternative indicator used to take account of variability in the different plant types, as well as possible outages and failures throughout the supply network. The de-rated capacity margin is the capacity margin adjusted to take account of the availability of plant,

specific to each type of generation technology. It reflects the probable proportion of a source of electricity which is likely to be technically available to generate, ignoring any commercial reasons that may cause a company to not utilise capacity (DECC 2011b). Due to this forecasting, there are *“always uncertainties in de-rated capacity forecasting due to the array of complex factors that feed into deciding on this capacity margin, due to its consideration of unforced outages from variable renewable energy sources”* (DECC 2009b). DECC, National Grid and Ofgem had suggested a range of 6-15% (DECC 2009b) likely de-rated capacity of the UK electricity supply network. However, in the “slow growth” scenario suggested in Chart 4.9 of the DECC report, there was a possibility of around 2% de-rated capacity margin in 2017, representing a potential risk to security of electricity supply. This is in support of this chapter’s presented scenario in that security of supply will be minimal between 2015 and 2018 at the very least if electricity supply and policy drivers do not align correctly. A 2% de-rated capacity margin suggests that the UK has a reliable capacity of only 64.8GW during a year where peak demand could be 63.6GW, based on this chapter’s presented scenario and not dissimilar to the largest peak demand that was seen in December 2010 of 60GW (Royal Academy of Engineering 2013a). It is important to add that the peak demand could be considerably more; uncertainties are again large in possible future demand (DECC 2009b). It is vital that any policy relating to emissions reductions and energy security are not weighted too heavily in either direction. However, based on this review it does not appear to be the increase in wind plant types that will cause the largest risks to energy security, but the delays in focusing on energy security and decisions on new dispatch able capacity. This will also be discussed further in relation to the nature of how wind farms generate intermittent electricity.

To summarise, the UK has a tough road ahead, both in meeting environmental targets and simple infrastructure targets. This delicate balance must be brought together in a way that equally weights all targets of a secure and low carbon electricity network so that one does not adversely affect the other.

### **3.4 Intermittency**

This section discusses assumptions that renewable energy plant types require 100% (or even close to 100%) backup due to their intermittency. This is also covered in greater depth in Chapter 7 in relation to resulting associated GHG emissions.



The issue of intermittency from having a large installed capacity (above 20% of total capacity) of wind (and in the future, possibly wave) projects has been raised as key to future decisions on how big a contribution variable renewable energy plants can make to total generation (Goodall & Lynas 2012). The following analysis draws on data from European studies of real wind farms and whole systems with wind playing a considerable role in meeting electricity demand. From a pragmatic point of view, intermittency necessitates a degree of back-up generation required to ensure security of supply of a system. This can be considered as an extra cost, both in monetary terms and energy (and even associated GHG emissions) terms, and can then be weighed up against the alternatives. Backup generation can be estimated and so an assessment can be carried out for decision-making since wind has played a role in a number of countries' electricity supply mixes for some time. An important element of wind power is that its "availability" during winter may be 17-24% as used by Ofgem compared to 85% for the range of gas plant on the system which is considered reliably available to meet demand (Royal Academy of Engineering 2013b). This is the amount of time the generating technology is operational and ready to generate divided by the amount time over the given period.

The capacity saving of renewable installations depends on the capacity credit. Relative Capacity credit is defined as the ratio:

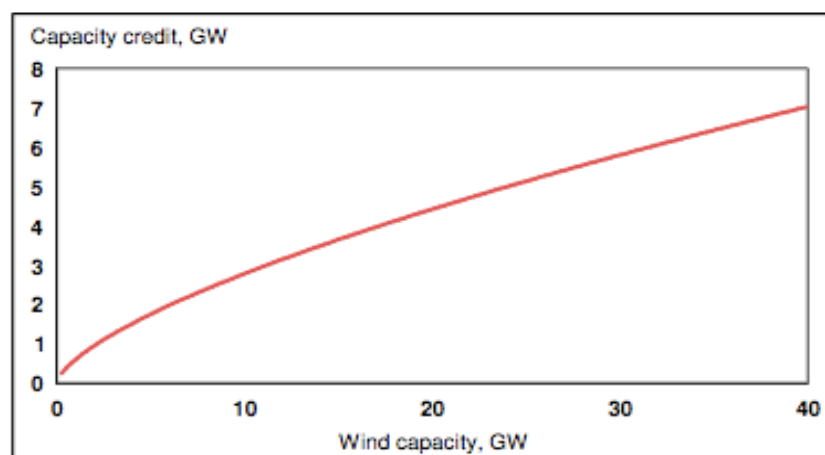
$$\text{Relative Capacity Credit} = \frac{\text{Capacity of thermal plant displaced}}{\text{Rated Output of Wind Plant}} \quad (1)$$

(Elliott et al. 2007)

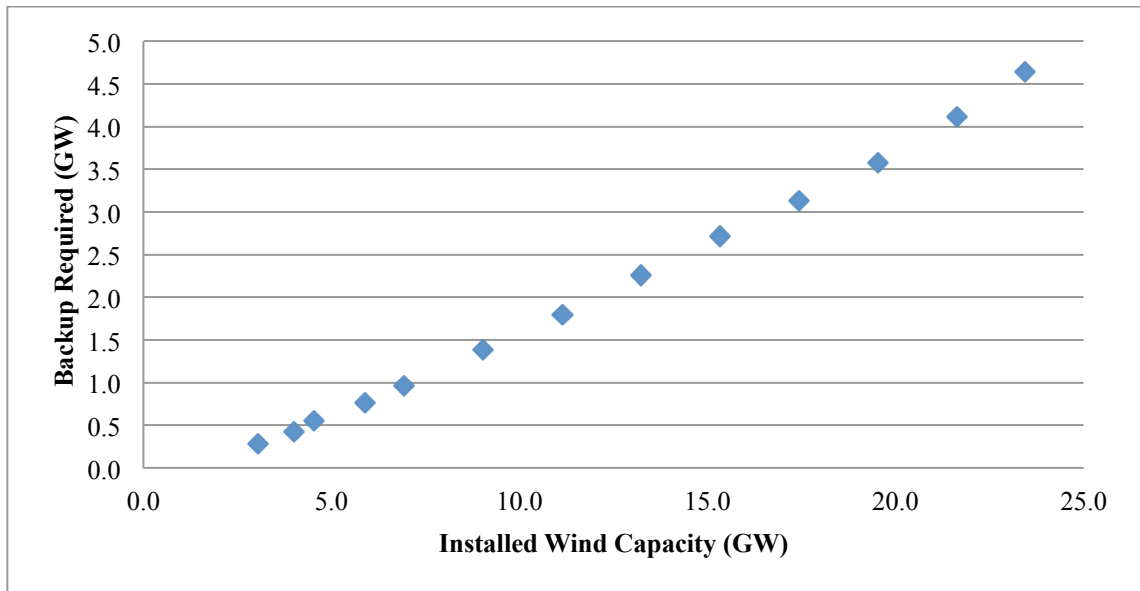
It has been suggested from a number of European-wide studies that this figure is roughly equal to the capacity factor which has been reported by DECC to vary between 24 – 35% with a long-term annual average of 27% for the UK with higher capacity factors favouring offshore installations and sites in higher wind speed regions such as Scotland (Sinden 2007a). This figure includes downtime due to maintenance, and forced outages due to mechanical failure. While this may be slightly higher than most onshore wind farms, it is also considered that in winter, wind power is displacing more thermal plant and so a relative capacity credit close to this does not seem unreasonable. This also supports a META review of wind farm associated GHG emissions estimation data

that show onshore wind farms to have capacity factors of 30% on average and offshore wind farms 40% capacity factors (Dolan & Heath 2012). The capacity credit for wind is clearly dependent on the capacity factor for wind and will naturally fluctuate between one year and the next, dependent upon the resource available throughout the year (Sinden 2007b). The capacity credit can also be described as the lowest output that can be confidently depended on as part of the total system capacity, or the amount by which conventional electricity generation methods can be removed from the grid while still maintaining a reliable grid. Instantaneously, this could be considered to equal zero, but over the course of a time period such as a year that is how capacity factor is considered in this instance, these would be roughly equal to the same figure provided availability was taken into account.

Figure 3.6 shows the relationship between wind power capacity to relative capacity credit, relating to UK capacity factors for wind power as already mentioned and as suggested by Milborrow (2009). 27% is taken to represent all wind power capacity factors that should be seen as conservative since offshore wind farms have larger capacity factors and are to increase in number over the coming decade. The graph used to find capacity credit as a function of wind capacity (see Figure 3.6) is a translated version that originates from a German study and refers to German installed wind capacity (DENA 2005). It was not possible to acquire a copy of the original document in English, but it has been cited widely (EWEA 2009). It should be noted that this graph represents installing wind farms in a large-scale grid such as those found in Europe. In other words, spare capacity already exists on the grid, as per traditional grid networks.



**Figure 3.6:** Capacity credit as a function of wind capacity (EWEA 2009)



**Figure 3.7:** Suggested backup required in addition to plant margin for installed wind capacities on the UK electricity network (2008 – 2020 installed wind capacity and projected added wind capacity)

The following equations are used in order to calculate the backup capacity required.

$$\text{Penetration} = \frac{\text{Average Wind Power}}{\text{Conventional power} + \text{Average Wind Power}} \quad (2)$$

$$\text{Backup Required} = \text{Average Wind Power} - \text{Capacity Credit} \quad (3)$$

**Where:**

$$\text{Average wind power} = \text{installed wind capacity} \times \text{capacity factor (27\%)} \quad (4)$$

$$\text{Capacity credit} = \text{installed wind capacity} \times \text{relative capacity credit (GW)} \quad (5)$$

*As suggested by (Milborrow 2009).*

	<i>Installed Wind Capacity</i>	<i>Wind Capacity factor</i>	<i>Average Wind Power</i>	<i>Conven- tional Capacity</i>	<i>Penetra- tion</i>	<i>Relative Capacity Credit</i>	<i>Capacity Credit</i>	<i>Backup Required</i>
2008	3.1	27.0%	0.8	79.1	1.0%	20.8%	0.64	0.19
2009	4.0	27.0%	1.1	78.6	1.4%	19.4%	0.78	0.30
2010	4.5	27.0%	1.2	78.5	1.5%	18.0%	0.82	0.41
2011	5.9	27.0%	1.6	77.5	2.0%	17.0%	1.00	0.59
2012	6.9	27.0%	1.9	76.9	2.4%	16.0%	1.11	0.76
2013	9.0	27.0%	2.4	75.2	3.1%	14.8%	1.33	1.11
2014	11.1	27.0%	3.0	73.5	3.9%	13.9%	1.55	1.45
2015	13.2	27.0%	3.6	71.9	4.7%	12.9%	1.72	1.86
2016	15.3	27.0%	4.1	70.2	5.6%	12.3%	1.89	2.25
2017	17.4	27.0%	4.7	68.5	6.4%	12.0%	2.10	2.61
2018	19.5	27.0%	5.3	66.8	7.3%	11.7%	2.29	2.99
2019	21.6	27.0%	5.8	65.1	8.2%	11.0%	2.40	3.46
2020	23.4	27.0%	6.3	63.8	9.0%	10.2%	2.39	3.94

**Table 3.1:** Wind farm capacity in the UK (real and projected) and resulting penetration, relative capacity credit, capacity credit and backup required, based on proposed scenario

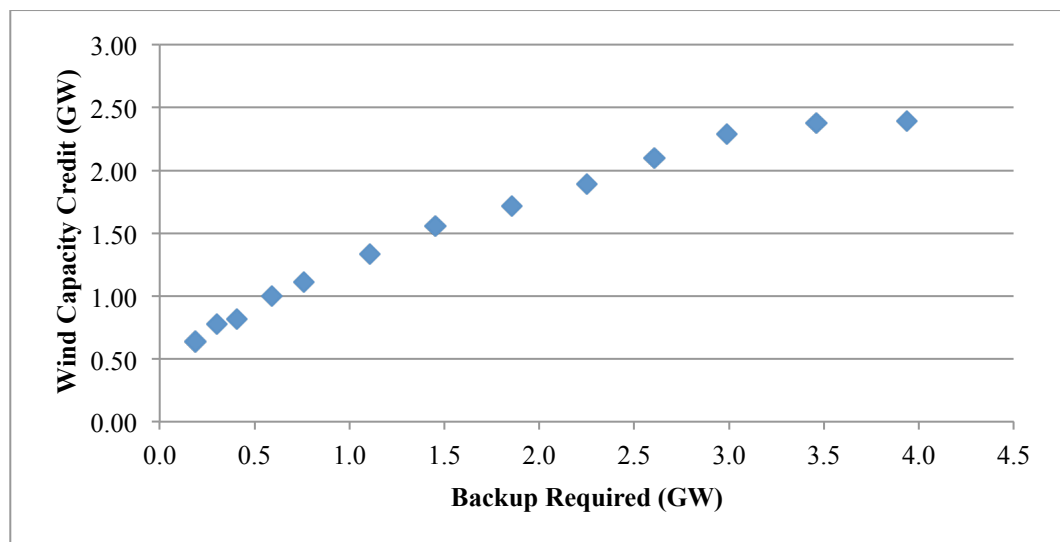
Figure 3.7 relates to real and projected data for installed wind capacity in the UK. Table 3.1 shows the calculations that have created Figure 3.7. It should be seen that the backup requirements of an intermittent power source such as wind power could be misinterpreted. While it is true that a single wind farm supplying an equivalent demand would require 100% backup were the output to equal zero, it is not the case when adding wind power to a system already designed with spare capacity and seasonal variations in demand. This is why the above figure shows that backup is not required until approximately 1.5GW of wind capacity is on the system. Even once this situation is passed, backup capacity can be supplied by the already present plant margin on the system. Indeed, thermal plant with a peak demand of 50GW for example will require considerably more installed capacity in order to maintain system reliability in order to meet variations in supply and demand, as in the case of the UK grid.

While opponents of wind power will argue that the above figures for backup requirements are unduly favourable to wind power, it has been seen in reality so far that including wind power in traditional systems at low penetrations does not require backup. Current traditional thermal plant and nuclear plant outages cause much greater disruption currently to large-scale electricity grids due to their relative size and that wind power outages can be planned for at least in the short term (Barnard 2013). It is important to comment however that once penetrations of wind power reach above 20% in a system, there may be a different picture in relation to backup due to the whole system's dependency on an intermittent source of electricity. It should not, therefore be

assumed that any intermittent source of power when integrated into a large-scale electricity grid will automatically require full backup generation. This point is emphasised in a newspaper article (Goodall & Lynas 2012) and will also be further expanded upon in Chapter 7 in relation to not only backup generation but interactions between generation technologies as they come on an offline. The UK currently has 14.8% (see Figure 3.3 above) of its electricity generation from renewables which are predominantly intermittent wind power and currently there are no plants that are specifically for backup of this; National Grid have so far managed to balance the system with already available capacity.

Figure 3.7 suggests that the UK will require a maximum of 3.9GW backup capacity if 23.4GW (30% of installed UK capacity). This would bring the total required installed capacity for 2020 to 91.1GW which is not significantly different to the current UK installed capacity of 89.2GW (DECC 2013).

Figure 3.8 shows how the required backup generation, relative to the total installed capacity, will increase less quickly as wind capacity increases.

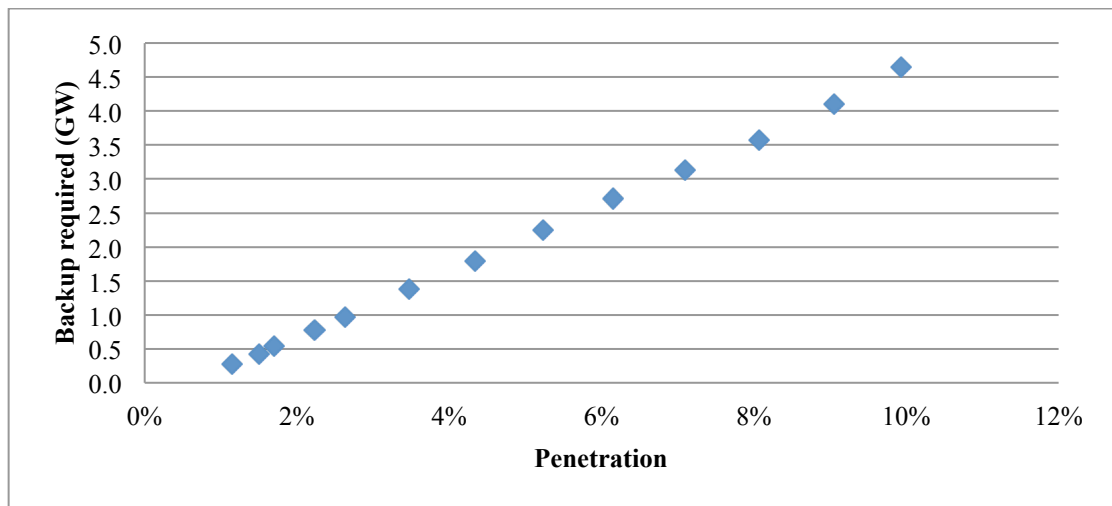


**Figure 3.8:** Backup required in relation to wind capacity credit in a UK context  
(Capacity credit = installed wind capacity x relative capacity credit)

The figure above suggests that an optimum wind capacity credit will be reached where greater and greater amounts of backup will be required while wind power's contribution will not increase. This equates to 21.3GW total installed capacity (approx. 23% penetration where penetration = average wind power divided by total installed

generation capacity on the UK grid – Equation (2), p53). This again supports the previous statements of likely backup and optimum wind penetrations on a grid system such as the UK.

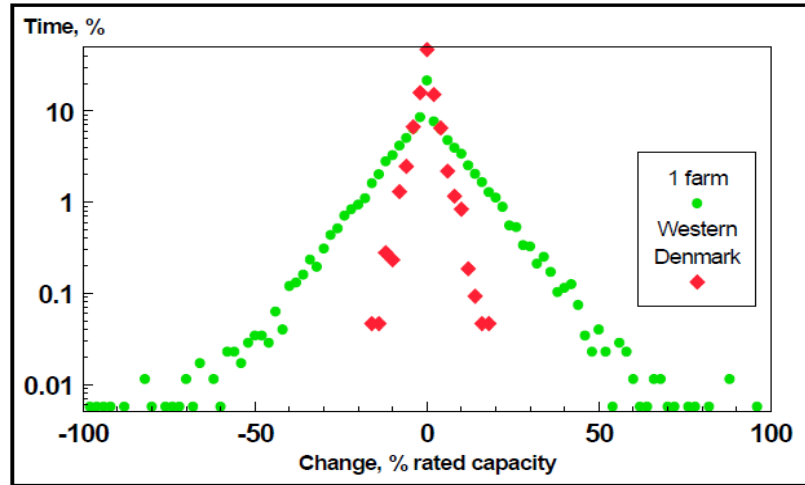
The following figure relates the penetration of wind on the UK electricity mix to the backup generation capacity required. Backup, as previously, relates to extra capacity, not already offered by spare capacity on the grid. This is accounted for in equation (2) due to conventional capacity being defined as total capacity less installed wind capacity in the UK.



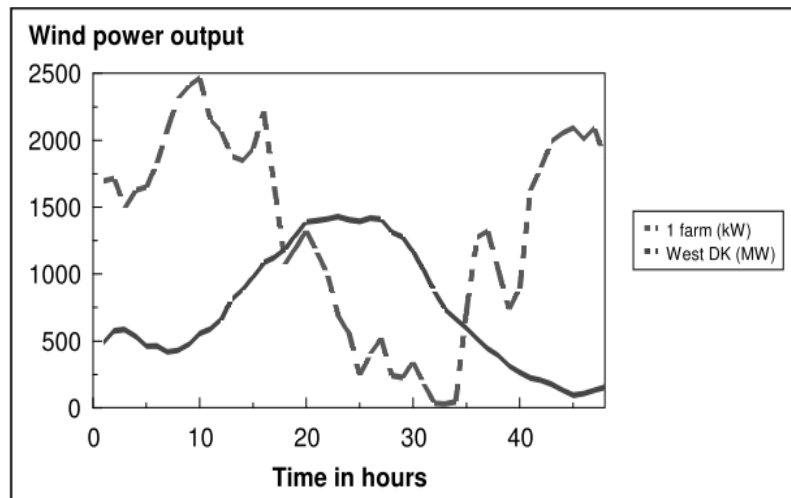
**Figure 3.9:** Backup generation required for different penetration levels of wind capacity in the UK

The figure above suggests that backup generation is linearly dependent upon the penetration of wind capacity to a system’s overall generation mix. Conventional capacity is taken to be the total capacity minus wind capacity for the UK electricity supply capacity.

The reason that backup generation increases less than penetration, as well as why nothing close to 100% backup generation is required can be explained by the above reasons but also from a number of European studies based on actual data and will be briefly presented below. It has links to the strong correlation between wind contributions and peak demand. Two figures can be used in order to show both the reduced uncertainty of wind power’s contributions to a whole system and the links between wind electricity supply and peak demand of a system.



**Figure 3.10:** Typical variations in output from one wind farm and for all wind in western Denmark (Milborrow 2009)



**Figure 3.11:** Changes in output of one wind farm, between two successive hours, compared with the same changes in the output of all wind plant in western Denmark. (Ford & Milborrow 2005)

Figure 3.10 shows how an integrated system behaves considerably better than that of a single wind farm. Figure 3.11 shows how changes in output are more manageable in a larger system.

These figures (3.10 and 3.11) show a favourable picture for wind power, but only used within a regional grid system. However, it should be noted that there is still large variability in wind power output. It is also unclear from the document whether the single wind farm is ‘typical’ as described by the author and especially with Figure 3.11; the individual wind farm chosen is unknown. It has been stated by the International

Energy Agency “*published studies of wind power find that integration of wind power at the levels considered so far do not need large backup capacities*”. (IEA 2005)

As mentioned previously and again here, there is even more optimism shown by some through comparison with the traditional capacities (Milborrow 2009):

*“Thermal plant breakdowns generally pose more of a threat to the stability of electricity networks than the relatively benign variations in the output of wind plant. Aggregation of wind outputs over the whole country ensures that the fluctuations are smoothed, in exactly the same way as the demands from consumers.”*

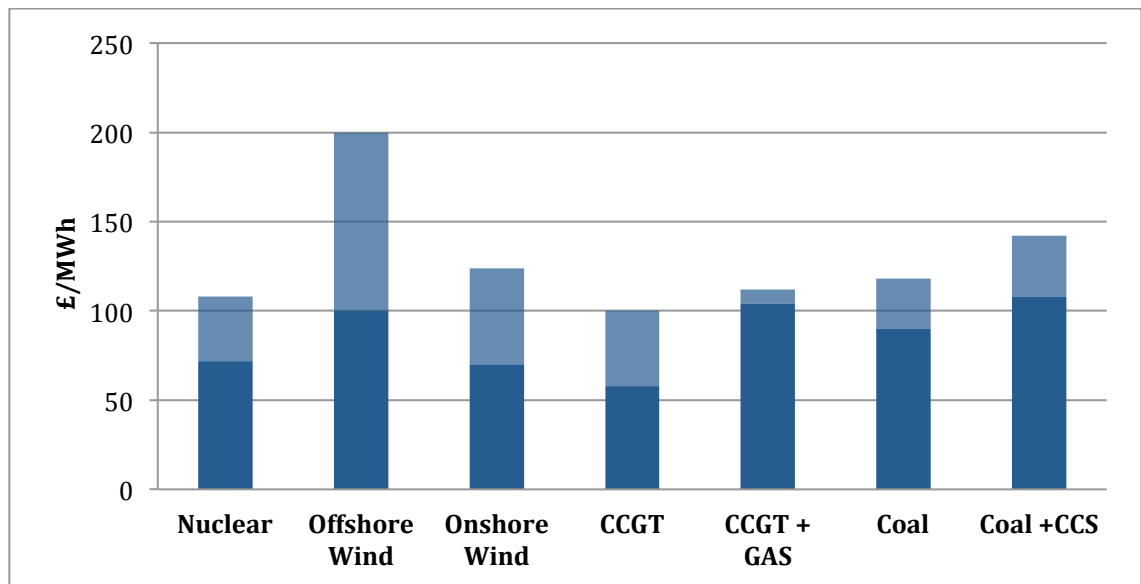
It has been demonstrated that there is an economical advantage to having abundant and cost-free electricity supply sources. Wind power has a relatively fast access time to market and generally stable life-cycle costs (Rechsteiner 2008). Wind cannot however offer decentralised solutions to electricity supply on its own, based on this information, unless very favourable wind conditions could be found for a specific site. Wind and other intermittent renewable power sources can play a key role in the UK’s future generation mix.

### **3.5 The Costs of UK Electricity**

The following section outlines the costs of different plant types and so suggests likely future costs for UK customers. As with all electricity generation projects, investments in supply capacities will be paid for by the customer, with the extension of renewable energy imposing significant financial burdens on societies (Peter & Lehmann 2008). It is stressed that due to the delays in decision-making, any further increase in current UK costs for a kWh of electricity is inevitable, due to the requirement for substantial investment in increased capacity.

Figures 3.12 compares the costs of current electricity generation options. These figures come from recent estimates from a variety of sources (UKERC 2013).



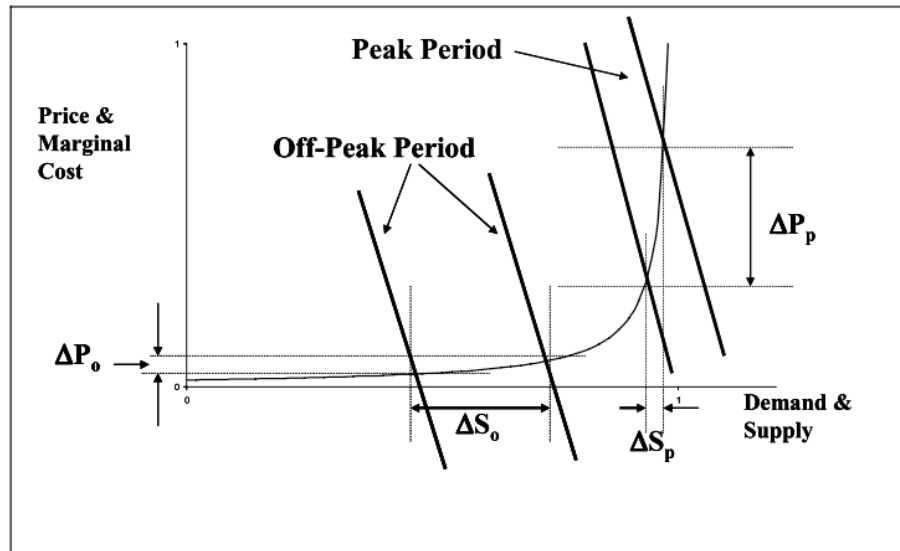


**Figure 3.12:** Range of recent cost estimates for large-scale electricity generation in the UK. Dark blue represents lower cost estimates, light blue the highest estimates of cost estimates (UKERC 2013; Figure 2.2).

It can be seen from Figure 3.12's cost comparison that offshore wind farms currently likely provide the most expensive electricity generated if the higher estimates are considered. This may be due to age of technology and location of sites, amongst other factors such as maintenance. It also represents the largest uncertainty in cost that may also be for similar reasons.

If gas is used more and more for backup capacity, its price per kWh will also increase, bringing wind and gas' relative prices for p/kWh closer. However, fracking in the UK may affect this situation in driving gas prices lower. However as already discussed, this thesis does not assume this to be the case due to recent news articles suggesting otherwise (Carrington 2013; BBC News 2014). This balancing act between wind power and gas power will be true in the UK, since hydroelectric power sources are generally considered to be at capacity and new energy storage options are still not economical and are predominantly still contained within the fossil-fuel stores of traditional thermal plants (Wilson et al. 2010). Currently, the UK electricity grid operates with sufficient levels of reserve due to conventional mixes of power plant types that are connected to the overall system (IEA 2005) although as discussed, these levels of reserve are reducing.

It has been suggested that the uncertainties and risks associated with the cost of generating electricity only covers half of the picture (UKERC 2007). These uncertainties and risks arise from a number of places, according to the report: variations in supply and demand (see Figure 3.13), traded price of gas and coal, factors affecting energy security, future policy and pricing associated with instruments of policy i.e. obligation credits or taxes etc.



**Figure 3.13:** The effect on price of electricity generated from small shifts in demand at peak and off peak (UKERC 2007)

It can be seen from Figure 3.13 above that small changes in the difference between supply and demand can have a huge impact on the price and marginal cost of electricity. While electricity network stakeholders understand this effect well, it is made more difficult by intermittent electricity generation that cannot be dispatched to meet demand. This dispatch ability of some technologies such as wind power have an effect on the efficiencies of other thermal plants on an electricity supply network, hence relative carbon intensity of electricity from thermal plants, will be further explored in Chapter 7.

The end customer will inevitably feel Price fluctuations of fuels used in electricity generation. As previously mentioned, it can be seen from Figure 3.3 that approx. 85% of UK electricity generation is still susceptible to fuel price changes, whether that be oil, natural gas, coal or uranium prices.

The UK Low Carbon Transition Plan (UKLCTP) set forward by the Government suggests that an additional average of 6% to household bills by 2020 will occur; with

climate policies this will be 8% as opposed to 15% to electricity bills and 23% to gas bills without the UKLCTP by 2020 (HM Government 2009). This clearly presents a case for rapid decarbonisation of the energy sector. As has already been presented, these figures also carry uncertainties that are difficult to estimate.

The Energy Watch Group report (Rechsteiner 2008) states that:

*“Capital intense power plants e.g. wind, photovoltaics, CSP or Hydro tend to be more expensive in the first 15-20 years. Once written off, cost per kWh drops to a variable cost level, normally of the cost of operation and maintenance. In case of wind power, a cost of less than 1-3 Cents per kWh can be observed because no fuel costs play in.”*

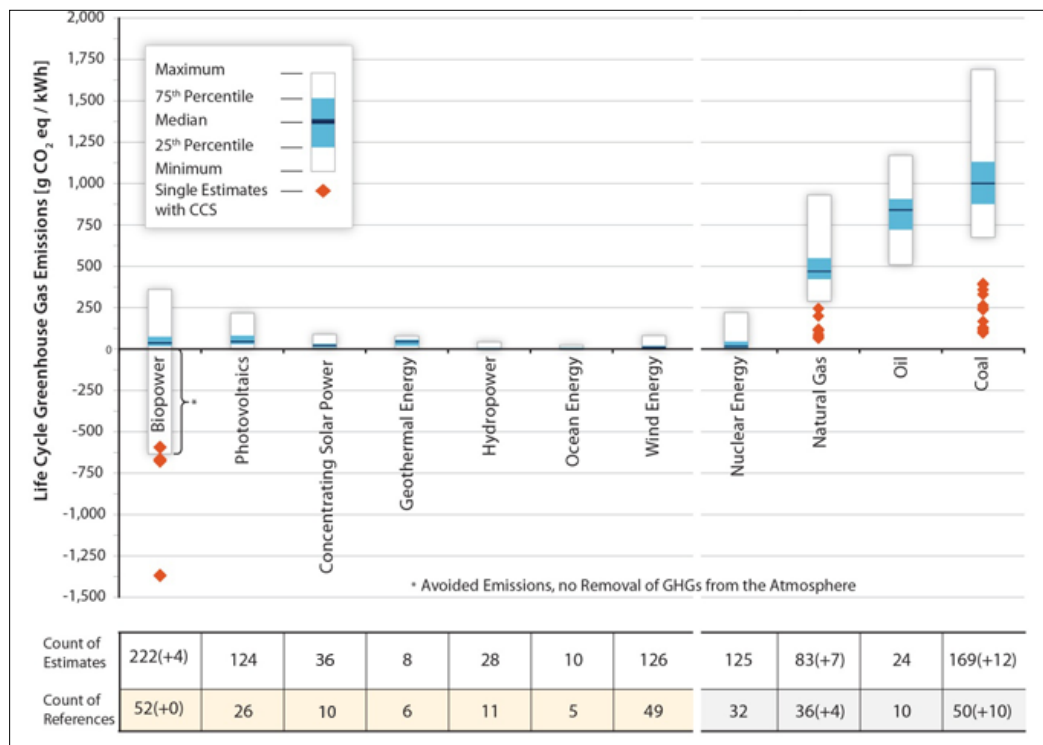
This statement may only be true however if relative life times of new technologies do not decrease such as wind power to 10 years for onshore and 15-20 years for offshore installations as suggested by Hughes (2012).

The issue however is that costs and profits for wind power have not taken a path currently that improves over time and Hughes (2012) would argue that since sites with good onshore wind resources are reducing, the average load factors that are achievable are reducing for example. This inevitably makes wind power less profitable overall. This may also be due to the relative age and development of wind technologies in that improvements are constantly being made while older turbines are still in operation but may be improved either in part or by replacing whole turbines. In terms of the case of Ormonde Offshore Wind Farm that is assessed in Chapter 6, the operator Vattenfall is contractually obligated to maintain availability of all its 150MW of wind turbines at over 98% throughout the year and for 20 years. This may have implications for the profitability of the farm if this requires steadily increasing maintenance costs year on year in order to ensure the same availability. The fact that maintenance costs increase over the lifetime of a project however is not exclusive to wind farms and indeed is consistent across all electricity generation technologies.

### **3.6 Life Cycle Greenhouse Gas Emissions**

The following section suggests life cycle GHG emissions for different technologies of electricity generation. Life cycle GHG emissions are those GHGs that are released as a result of all activities relating to the project or technology in question, through out its

life time from conception to decommissioning. Chapter 4 will review life cycle emissions and the associated methodologies for determining them in more depth. Figure 3.14 shows life cycle GHG estimates for a range of electricity generation technologies, as reported by the National Renewable Energy Laboratory (NREL). Figure 3.14 shows that fossil fuel based technologies have significantly larger associated life cycle GHG emissions than other electricity generation technologies. This Figure 3.14 also shows the number of estimates that have created these ranges that generally reflect the ages of technologies and research into their associated life cycle GHG emissions.



**Figure 3.14:** Life Cycle Emissions for different electricity generation technologies (NREL 2012)

Clearly, by their nature, renewable technologies, as well as nuclear, have relatively low life cycle GHG emissions to thermal plants that have large associated GHG emissions. The following two chapters (firstly in terms of life cycle assessment in general in Chapter 4 and then specifically to wind in Chapter 5) will discuss in more detail the reasons for the displayed ranges of estimates.

It should be mentioned that while ocean energy appears most favourable in terms of associated life cycle carbon emissions, this is based a low number of estimates and even fewer references. This is a product of the relative age of the technology but also perhaps

telling in that there is still not consensus on types of commercial scale technologies and also that current estimates of levelised cost of electricity from the ocean energy industry itself vary between 25 and 63 c/kWh (Euros) depending on whether it is wave or tidal technology and current uncertainties (SI Ocean, 2013; Figure 2). Comparing this to Figure 3.12, this highlights how difficult ocean energy technologies are to include in realistic electricity generation plans at present since they are at best 4.5 times more expensive than even offshore wind but worst case, they are 11.5 times more expensive (based on an exchange rate of 0.8 £/€).

### **3.7 Conclusions**

The Kyoto Protocol has been a driver for UK carbon accounting policy for many years now but has now expired. In terms of targets, the UK has succeeded so far in its required reductions, although it has been shown that these changes have not come from the premise of GHG emission reduction, rather the price and availability of gas supplies and the technical advantage of efficiency improvements to turbine and power station performance (DECC, 2009a; Annex E. Section E.15). Unlike the overall increasing of CO<sub>2</sub> emissions in the UK, emissions associated with power stations have decreased by around 25Mt CO<sub>2</sub> since 1990. It is considered by some that the Kyoto Protocol has failed to provide the changes that it was designed to achieve (Prins et al. 2010). This could be partly to do with issues discussed in Chapter 1 where uncertainty from some still surrounds the certainty of IPCC predictions and denial over Peak Production issues, although many other factors also will have undoubtedly been influential.

In the development of the UK's electricity supply networks, it has been so far accepted that direct emissions are the critical component for evaluating associated emissions from power plants. Indeed, efficiency improvements and fuel choices reduced UK CO<sub>2</sub> emissions by 32.5% by 2008, relative to what they would have been without the changes from the 1990 UK Kyoto base year (DECC 2009a).

Energy generation, security and cost are all linked. Life Cycle Assessment gives a figure for the environmental cost to produce one unit of electricity. This life cycle GHG emission estimation can be used to track energy use through a project (or the electricity use and associated resource use through a project). It will take a shift in company policy and customer desire to want to produce or demand electricity from a supplier

who can produce their unit of electricity for the least whole life cost in terms of GHGs (energy and resource use) unless it also has financial benefits.

Contrary to some doubts over reaching the 2020 targets of 30-35% electricity from renewables including rather startling headlines such as it being impossible to install the required capacity from wind farms due to the huge task of installing 10 turbines a day (Fells & Whitmill 2008), it is deemed feasible by Government and other commentators that the 2020 renewable target for electricity generation can be met. It can be seen from the scenario presented in this chapter that wind alone could get close to the target.

In terms of the type of generation technologies that will predominantly make up our energy mix, life cycle assessment will become increasingly important to track indirect emissions. Renewables, namely wind power in this instance, can provide the targeted 2020 generation contributions. This is without considering a hydroelectric contribution, and considering a large reduction in nuclear contributions from planned closures and slow feed-in times.

GHG emissions reduction should not be the key driver for electricity generation policy but rather part of the decision. Energy security, assessed by de-rated generating capacity should be key driver in order to ensure sufficient supply. Without a secure energy future, there will be less economic ability to afford to reduce GHG emissions.

Given that as wind's contribution increases, its relative capacity credit decreases, it should be recognised that a diverse electricity mix is of crucial importance. This will lead to greater security of supply. It does not seem feasible or cost effective to attempt to meet all electricity targets with only wind or a similarly intermittent technology.

Chapter 4 will highlight how important it will be to have a standard carbon accounting methodology that can assess all potential electricity generation technologies and effectively compare their whole life emissions characteristics.

## Chapter 4 – Life Cycle Greenhouse Gas Assessment in the Energy Sector

This chapter introduces life cycle GHG estimation for products and services in the energy sector. Current literature around life cycle studies is outlined and specifically, the International Standards Organisation (ISO) Life Cycle Assessment framework is introduced. It is shown to be a framework that stops short of providing an assessment standard method for stakeholders who are not aware of issues surrounding the estimation methodology. In order to confidently compare technologies and aspects of their life cycle, a well understood standard assessment method must be in place for decision-makers. Key criteria that affect a life cycle study are presented and they are discussed in relation to the energy sector and different power generation technologies. Historic life cycle studies should be assessed based on their system boundaries, the assumptions made, the data used, the ability to utilise the GHG emissions figures for reduction, the methods of displaying uncertainties in the results and their transparency throughout the assessment process. These are discussed in detail. The fundamental importance of standardising the life cycle GHG assessment methodology is clearly shown, based on these key problems within the ISO LCA framework and further work is suggested to formalise this assessment for the power sector.

### 4.1 Introduction

*“At present there is no carbon accounting system in Scotland that can ensure that a real reduction in emissions is being achieved and not displaced to other countries, therefore making it very difficult to assess future progress.”* (Barrett 2009)

While this quote refers to Scotland, in the UK, Europe and globally, the issue is the same. Carbon assessment, carbon accounting, carbon footprinting, life cycle greenhouse gas analysis, life cycle carbon assessment; these expressions are all used, often interchangeably, to explain the process by which the total amount of carbon dioxide (and other GHGs such as methane) emissions associated with a product, service or even individual can be calculated. Practitioners have their preferences and indeed, some believe that some or all of these expressions are inaccurate, depending on the assessment. Firstly, it is not simply carbon or indeed carbon dioxide that should be

counted over the lifetime of the product (or service). Secondly, some of these expressions require further definition in order to clarify the time-periods they consider. It is for these reasons that for the purpose of this review and as a proposed suggestion in line with LCA practitioners, the expression “life cycle GHG assessment” will be adopted. This is because it shows both the specific time frame considered, i.e. the total life cycle without compromise, and also that it considers all gases that have a global warming impact.

Life cycle GHG assessment exists in numerous forms for all of the sectors of the UK economy. The Climate Change Act 2008 set out the requirement for such an assessment and has led to numerous guidance documents on the specific approaches for individual sectors. While being crucial for the progression of life cycle GHG assessment and the understanding gained through the procedure for reducing associated GHG emissions, the weight of guidance has led to confusion over best practise and the lack of a standardised life cycle GHG assessment approach. This comes at a time when policy and economic decisions are being made based on associated GHG emissions for different technologies and fuel mixes that still contain large uncertainties (Weber et al. 2010).

This situation has resulted from the policies outlined by the European Union (EU) which have in turn fed into national policy for the deployment of renewable technologies to meet associated carbon emissions reduction commitments (European Parliament 2008). The UK’s main policy document for reducing GHG emissions, the Climate Change Act 2008, has the following key aims:

- Improve carbon management, helping the transition towards a low-carbon economy in the UK;
- And demonstrate UK leadership internationally, signalling that the UK is committed to taking their share of responsibility for reducing global emissions in the context of developing negotiations on a post-2012 global agreement at Copenhagen in December 2009 (although no binding agreement was made).

This Act is the driver for strategies for the UK as a whole to move to a low carbon economy. The most important aspect for this research being strategies to reduce the GHG intensity - the amount of GHG emissions associated with production and supply of 1kWh of grid electricity. Clearly, life cycle GHG assessment of electricity supply should echo the aims set out by the Act and the documents born from these. The Act



mentions Copenhagen, the 2009 United Nations Climate Change Conference, since it was expected that international legally binding agreement would be reached. However, this was not the case and there are still no legally binding global targets. A regulatory gap now exists as the Kyoto Protocol commitments ended in 2012. However, it was agreed at UN talks in Doha to extend the legally binding Kyoto Protocol for tackling rising GHG emissions to 2020. It covers Europe and Australia, whose associated emissions equate to only around 15%. It has been reported that while this helps to lay foundations for a new global deal by 2015, with strong new principles surrounding the wealth divide for many countries, few actual GHG emissions reductions commitments have been agreed but the US, China and EU still have varying degrees of reservation (Harrabin 2012).

This chapter intends to formally identify the key characteristics that a life cycle GHG assessment should have for ensuring effective policy and also technological achievement in relation to assessing associated life cycle GHG emissions resulting from electricity generation. Due to there being no single standardised approach to life cycle GHG assessment in place, it will be shown that a lack of clarity and consistency still exists. The most common approach to life cycle GHG assessment for electricity generation infrastructure is to follow the life cycle assessment principles and framework outlined by the ISO and adopted as a European and British Standard, BS EN ISO 14040-14044:2006. This considers a number of other impact categories, as well as global warming potential (GWP) from greenhouse gases, but this thesis is primarily concerned with the GWP impact category. Nevertheless, lessons can be gained from the on-going discussions on ISO LCA in order to improve life cycle GHG assessment practice. To obtain comparable accounts of GHG emissions across the electricity generation sector, it is essential to have a standard approach adopted by all members of the sector and an understanding of the technology or technologies being assessed. The basis of this is therefore in place with an internationally recognised standard framework, albeit not technologically specific. It will be shown, however, that there are still a number of unresolved issues. It is shown that while life cycle assessments (LCAs) and life cycle GHG assessments are being carried out, it is still difficult to compare two LCAs in relation to any impact category, such as GWP, due to a number of key characteristics in the assessment framework that lead to problems throughout the methodology. This is especially shown in the large variations of historic nuclear power LCAs that is not simply a result of the natural variations between site-specific studies

(Sovacool 2008). It is believed however that the majority of these problems can be removed when applying a methodology to a given sector for a given impact category, once key criteria are understood (Heath & Mann 2012). Once the key criteria influencing LCAs are known, they can be used to review historic LCAs (and life cycle GHG assessments) and define standards for future assessments. This highlighting of key criteria and review of historic LCAs is conducted in Chapter 5 and shows a META-Analysis of Wind Power LCAs. However, before this can be done, a better understanding of ISO LCA is required and forms the premise for this chapter's review.

LCAs differ (in methods and assumptions) often for legitimate reasons, but their inconsistency hampers direct comparison of the results. The LCA Harmonisation Project developed a META-analytical procedure called "harmonisation" which adjusted the previously published GHG estimates to ones based on a more consistent set of methods and assumptions. Each harmonisation article took slightly different approaches, demonstrating the flexibility of the harmonization approach (Heath & Mann 2012).

Firstly, the aims and objectives of this review will be outlined. Secondly, life cycle assessment and carbon life cycle assessment methodology will be introduced along with terms and definitions required to conduct these environmental assessments. Finally, the current problems in ISO LCA will be presented and suggestions made as to how these problems can be resolved in relation to standardisation of life cycle GHG assessment in the power sector.

## **4.2 Aims and Objectives**

From the review of papers that discuss life cycle assessment and specifically ISO LCA, the most up-to-date state of LCA available to assessors will be presented. Previous studies into the effects of methodological choice on life cycle assessments, including impacts on values for different phases of the life cycles, will show why this review is important as well as presenting current knowledge on the effects of methodological choice within the LCA framework.

This chapter will present the key problems in ISO LCA and current knowledge on characteristics of different methodologies in LCA. This will allow for the critique of

historic assessments in future research in order to standardise life cycle GHG assessment for technologies in a given sector, in this case electricity supply infrastructure in the power sector. The framework must be robust and suitable for all technologies and so the key characteristics that create problems within a GHG life cycle assessment must help towards this requirement.

### **4.3 Method of Article Review**

The following specific research questions will be addressed in this review:

1. Can common problems in life cycle assessment be outlined in order to eliminate them in relation to a specific sector and its activities?
2. Can historic LCAs be critiqued in relation to a later defined set of key characteristics (resulting from a highlighting of the problems in LCA) of the ISO LCA framework?
3. Can an improved standard framework be outlined for electricity supply technologies currently in operation or scheduled to contribute to UK electricity generation in the near future?

A systematic search of the published literature was conducted in order to find all literature related to carbon and GHG assessment of electricity supply technologies. This was done with a pre-determined list of various combinations of the following keywords: Life Cycle Assessment, carbon accounting, carbon assessment, energy, energy sector, electricity supply, electricity generation technologies, process analysis, carbon analysis, greenhouse gas analysis, life cycle analysis, input-output analysis. These keywords were from prior knowledge of the research area and exposure to other literature on the subject. Bibliographies of literature obtained were also used to identify any other references that might not have otherwise been found. Only originals in English are considered in this study. Other inclusion parameters include relevance of the article to the research aims and objectives.

A valuable resource was the LCA discussion email list, which provided a platform to quickly obtain relevant literature.

## 4.4 GHG life cycle assessment in electricity supply infrastructure

### 4.4.1 Stakeholders

The electricity market has an impact on all parts of the economy, whether it is small to medium Enterprises (SMEs), multi-national corporations or homeowners. However, it is important to also outline some key stakeholders in the power sector. The electricity market can be categorised into three stakeholder areas: the **generators**, such as E.ON UK; the companies involved with electricity **distribution** who are National Grid in the UK; and the **suppliers** who mainly interact with customers of electricity such as British Gas (National Grid 2009). Surrounding this framework of stakeholders are investors and government who are concerned with the effective delivery of both energy security and carbon reduction.

### 4.4.2 The Methodology

“Without an environmental management framework, an audit will have minimal results and therefore cannot assure a [project and its leaders] that its performance is meeting legal and policy requirements” (Emery 2003). It could also be considered that results may also be as uncertain as they are minimal since results may exist but that they are misrepresentative of the project or system in question.

The most important parameter of life cycle GHG assessment is that it considers the whole lifespan of a product or service. It must consider all phases of an electricity generation technology and transmission grid from its initial conception, through construction and operation to decommissioning. The most developed method of calculating the environmental impacts of a product or service is life cycle assessment. Life cycle assessment is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 2006a). LCA is a relatively young practice that was developed in the mid-1980s (Finnveden et al. 2009) but has more recently become a recognised approach to evaluating both present and potential decisions. Specifically here, LCA offers a standardised framework (ISO 14040-14049) for the assessment of electricity generation technologies in terms of their impact on the environment through a number of different characterisation factors. These are climate change (global warming potential), acidification, marine eutrophication, photochemical oxidant formation, particulate matter formation, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity. Life cycle GHG assessment can be seen as a sub-component of

environmental assessment (Emery 2003). Therefore, while this chapter only concerns itself with life cycle GHG intensities of electricity supply, important lessons must be taken from LCA since it has developed into an internationally agreed standard. However, aspects of LCA are still in need of clarification throughout the four phases (below) of LCA (Finnveden et al. 2009) and the uncertainties associated with choices throughout these phases must be understood and well presented in order to provide decision makers with a transparent, honest assessment (Heijungs & Huijbregts 2004). The current discussion on the issue of choices throughout the phases of LCA and the ways by which to show uncertainties and sensitivities associated with these are a good starting point for the development of a life cycle GHG assessment tool for UK electricity supply.

There have been numerous papers published on the virtues of LCA for driving policy decisions through accurately assessing different electricity generation technologies and their ability to mitigate the increase in carbon dioxide emissions into our atmosphere (Meier 2002; Kenny et al. 2010; World Energy Council 2004). However, there is also criticism of ISO LCA's framework in that it allows too great an amount of subjectivity. This indicates its cut-off criteria which specifies of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study in the allocation of associated emissions to processes and so little confidence can be given in comparative LCA studies (Suh 2004). While these comments came before the most recent version of ISO's standards, similar unresolved problems have been reported on the most recent version of the standard (Reap et al. 2008a; Reap et al. 2008b).

As summarised in the review of Life cycle assessment (LCA) by Reap et al. (2008a and 2008b), the tool remains the most developed and used for estimating environmental effects caused by products and processes throughout their life cycle. However, while now being used by many practitioners and outlined by ISO standards, "life cycle assessment is a tool in need of improvement". The ISO standards are the common benchmark for life-cycle study. However, they are "not intended for contractual or regulatory purposes or registration and certification" (ISO 2006a). While this is mentioned early in the standard, it is already being used as a framework for conducting LCA studies in general and as such carries a good deal of importance for environmental

assessments. There is also no specific guidance on how to review current LCAs in a systematic way in relation to best practice (Zumsteg et al. 2012).

As will be discussed further in the results of this review, 15 major problems are identified by Reap et al. (2008a and 2008b) in these four phases of LCA. Identification of these issues will aid in reducing these problems and it is believed that these can be addressed and reduced by focusing on LCA within a specific sector (here the UK power sector) and a specific impact category (here global warming potential). Of course, this is not a full LCA, but rather a GHG life cycle assessment. However, for the purposes of this review and for proposing a standard life cycle GHG assessment methodology for the power sector, this is of critical importance.

#### **4.4.3 Definitions**

Firstly, to study the current state of life cycle GHG assessment in the UK power sector, some important definitions are outlined. For this review, the following definitions have been taken from ISO (2006a) and also from other sources where it is deemed that additional clarification is required. These are shown at the end of the definition list below.

- A. **Functional Unit** – quantified performance of a product system for use as a reference unit. In this case 1kWh of electricity delivered to the grid by a power generation technology.
- B. **System Boundary** – set of criteria specifying which unit processes are part of a product system
- C. **Product** – any goods or service
- D. **Co-Product** – any two or more products coming from the same unit process or product system.
- E. **Unit Process** – smallest element considered in the life cycle inventory analysis for which input and output data are quantified.
- F. **Process** – set of interrelated or interacting activities that transform inputs into outputs.
- G. **Input** – product, material or energy flow that enters a unit process.
- H. **Output** – product, material or energy flow that leaves a unit process.
- I. **Raw Material** – primary or secondary material that is used to produce a product
- J. **Product Flow** – products entering from or leaving to another product system.

- K. **Product System** – collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.
- L. **Allocation** – partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems
- M. **Cut-off criteria** – specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study.
- N. **Potential Environmental impacts** – relative expressions, as they are related to the functional unit of a product system.  
*In this case (gram of CO<sub>2</sub> per kilowatt hour) gCO<sub>2</sub>/kWh*
- O. **Life Cycle** – consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.
- P. **Life cycle assessment** – compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.
- Q. **Comprehensiveness** – LCA considers all attributes or aspects of natural environment, human health and resources. By considering all attributes and aspects within one study in a cross-media perspective, potential trade-offs can be identified and assessed.
- R. **Transparency** – open, comprehensive and understandable presentation of information
- S. **Uncertainty Analysis** – systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability.
- T. **Sensitivity Analysis** – systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study
- U. **Data Quality** - characteristics of data that relate to their ability to satisfy stated requirements

The following definitions have been adapted from additional sources that are given in each instance.

- A. **Life Cycle Greenhouse Gas Assessment** – compilation and evaluation of the inputs, outputs and the potential global warming potential of a product system throughout its life cycle. Author's own adaption of LCA definition

- B. **Embodied carbon** – the carbon [carbon dioxide and equivalent GHG] emissions emitted in the creation [and maintenance] of any product or service over its lifetime. This is the primary factor in determining the carbon mitigation potential of a technology (Hondo 2005).
- C. **Embodied Energy** – the energy used in the creation [and maintenance] of a product or service over its lifetime. *Author's own adaptation of above definition.*  
*Or Embodied energy* - the total primary energy consumed during resource extraction, transportation, manufacturing and fabrication of a product (Hammond & Jones 2008).
- D. **Marginal Supply** – the changes in production given the combination of power plants and their individual marginal production costs *and marginal carbon intensities.* (Lund et al. 2010) *and author's adaptation.*
- E. **Marginal emissions factor (MEF)** – The carbon dioxide (CO<sub>2</sub>) emissions reduction afforded by a demand-side intervention in the electricity system is typically assessed by means of an assumed grid emissions rate, which measures the CO<sub>2</sub> intensity of electricity not used as a result of the intervention. (Hawkes 2010)

An important distinction should also be made between **uncertainty** and **variability**, as outlined out by Reinout Heijungs & Huijbregts (2004):

- **Uncertainty** relates to a lack of knowledge or data or that the data available is either wrong or ambiguous.
- **Variability** in contrast describes the homogeneity of data.  
 Homogeneous data is also called averaged data by LCA practitioners (Finnveden et al. 2009). This will be discussed further.

The outlining of definitions is as important to the carbon and energy assessment arena as it is to this chapter due to the misuse of many terms both within the sector and indeed elsewhere, especially in the media. This further leads to confusion and a lack of confidence in carbon accounting.

#### 4.5 The Grid Carbon Intensity Factor

GHG life cycle assessment is logically the first step to a GHG emission reduction strategy. The UK power sector – electricity supply infrastructure and technologies, and their associated GHG emissions from electricity production at UK power stations – accounts for an estimated 33% of UK GHG emissions (DECC, 2013; section 5.50). It is therefore crucial that the associated GHG emissions from the life cycles of all available



electricity supply technologies are known and understood. The power sector is also unique in that its associated carbon intensity filters down through the entire economy to every electricity-using product or service and into every organisation's carbon accounts. This means that the carbon intensity figure for UK grid electricity needs to be accurate and trusted by all other sectors. The carbon intensity for UK **consumed** grid electricity has been estimated as 0.491 kgCO<sub>2</sub>/kWh (Defra/DECC 2013a). This figure represents UK grid electricity's carbon intensity resulting from UK power stations, at the point of use, i.e. at the plug socket. If imported electricity is included, this factor drops to 0.485 kgCO<sub>2</sub>/kWh due predominantly to France's imported electricity being less carbon intensive than the UK's due to its reliance on nuclear power.

The UK GHG emissions factor for electricity consumed represents a combination of the emissions directly resulting from fuel use in electricity generation and from electricity grid losses i.e. the average CO<sub>2</sub> emission from the UK national grid per kWh of electricity generated. These relate to Scopes 2 and 3 from the GHG Protocol (World Resources Institute 2007) which cover direct emissions of GHGs at UK power stations with imported electricity factored in. The GHG emissions factor changes from year to year, as the fuel mix consumed in UK power stations changes. Because these annual changes can be large (the factor depends very heavily on the relative prices of coal and natural gas), and to assist companies with year-to-year comparability, a 'grid rolling average' factor has been presented which is the *average* of the grid Conversion factor over the last 5 years. This factor is now replaced with the in-year average (i.e. non-rolling average) as of 2013 (Defra/DECC 2013a).

The GHG emission factors include only carbon dioxide, methane and nitrous oxide emissions at UK power stations, with the Indirect GHG emission factors including the emissions resulting from production and delivery of fuel to these power stations (i.e. from gas rigs, refineries and collieries, etc.) not being included (Defra/DECC 2013b). However, these fuel lifecycle emissions have been estimated and presented as the percentage of total CO<sub>2</sub> emissions by fuel of 15.9% (Defra/DECC 2013b). This equates to 0.0703 kgCO<sub>2</sub>e of 2013's GHG emissions factor. It is not required to use this factor for the fuel lifecycle but as discussed in Chapter 2, it seems counter-productive to not include this since it represents a significant consumption of fossil fuels in the lifecycle.

The factor also includes upstream emissions from extracting, processing and distributing electricity to the final user, but does not include emissions associated with transportation of fuels. This omission may seem to be acceptable at present with coal mining and transport only accounting for 0.8% of the total associated life cycle CO<sub>2</sub> emissions for typical UK coal power stations (Odeh & Cockerill, 2008; Table 6). However, it could also be seen as unacceptable in nuclear power's case since transport of uranium alone accounts for 11% of the total life cycle CO<sub>2</sub> emissions (Torness nuclear power station receives its uranium from Olympic mine in Australia (British Energy 2006)). This is one such example of a need for standardisation of system boundaries and allocation of environmental impacts across all technologies. Another example is embodied GHG emissions in materials used to build power generation technologies and infrastructure, especially as more capital-intensive renewables enter the electricity mix. For example, the largest contribution to total GHG emissions of onshore wind farms (not built on peat bogs) results from the raw material production and manufacturing phase of the life cycle (approximately 90%) (Dolan & Heath 2012). Indeed this is true for every impact category within the LCA framework (D'Souza et al. 2011). In order to make the best decisions, a standard framework should be in place that captures these differences in GHG life cycle emissions characteristics within a sector for a given impact category and especially GHG emissions in this case and in meeting EU and UK targets.

While some discuss the differences in choosing specific carbon (carbon dioxide and GHG) intensities over grid average intensities in some instances (Mathiesen et al. 2009), others argue that the fact that once electricity leaves the generation technology to enter the grid, it is impossible to know where exactly the electrons travel to so to promote the idea of specific grid intensities appears illogical and inaccurate (Weber et al. 2010). While this thesis focuses on the associated emissions of electricity entering the grid, it is also concerned with electricity at point of use and only when electricity is supplied by a specific technology to a specific user, should that marginal data for that technology be used (Weber et al. 2010). However, the use of accurate marginal emissions factors would improve the decision-making process since they better estimate the relative merits of GHG emissions strategies (Hawkes 2010). This is also difficult for decision makers since specific carbon intensities for specific time periods could drive competition and interest from users into technologies with low carbon intensities per kWh. The Fuel Mix Disclosure regulations are specific to the electricity industry and

require the average quantity of CO<sub>2</sub> produced per kWh generated to be published. With no standard approach, however, this relies on the companies concerned and the ISO standards to ensure that this data is accurate. The Fuel Mix Disclosure regulations cover production emissions and so set nuclear and renewable power's carbon intensity to zero. In terms of life cycle emissions, this is inaccurate and would not improve any aspects of these technologies with respect to their life cycle emissions. To ensure the step change that is required, this will have to change.

## 4.6 Results

### 4.6.1 Overall Assessment of Papers

Table 4.1 shows an overview of papers considered, including the areas within LCA that they specifically discuss.

Reference	LCA theory	Analysis
(Finnveden et al., 2009)	Key Criteria of LCA	LCA
(Frischknecht & Stucki, 2010)	Key Criteria of LCA	Attributional and consequential LCA
(Weidema, T Ekvall, & R Heijungs, 2009)	Key Criteria of LCA	Consequential LCA and Hybrid LCA with IOA
(Reinout Heijungs & Huijbregts, 2004)	Key Criteria of LCA	LCA
(Kenny, Law, & Pearce, 2010)	Key Criteria of LCA	Dynamic carbon assessment using LCA
(S Suh, 2004)	Key Criteria of LCA	Hybrid LCA with Input Output Analysis (IOA)
(S Suh et al., 2006)	Key Criteria of LCA	System boundary allocation within LCA framework and hybrid IOA
(Weber, Jaramillo, Marriott, & Samaras, 2010)	Key Criteria of LCA	LCA
(Lund, Mathiesen, Christensen, & Schmidt, 2010)	Key Criteria of LCA	Consequential LCA
(T Ekvall, Tillman, & Molander, 2005)	Key Criteria of LCA	"Prospective" vs. "Retrospective"
(Reap, Roman, Duncan, & Bras, 2008a)	Key Criteria of LCA	ISO LCA

**Table 4.1:** 28 studies considered in reviewing life cycle assessment (1)

<b>Reference</b>	<b>LCA theory</b>	<b>Analysis</b>
(Reap, Roman, Duncan, & Bras, 2008b)	Key Criteria of LCA	ISO LCA
(Lloyd & Ries, 2007)	Key Criteria of LCA	LCA uncertainties
(Finnveden, 2008)	Key Criteria of LCA	"Attributional" and "consequential" LCAs & data choice
(S Suh & G Huppes, 2005)	Review of Methodologies	LC Inventory compilation
(Frischknecht et al., 2007)	Review of Methodologies	LCA and Ecoinvent database
(Jiusto, 2006)	Review of Methodologies	Carbon emissions accounting, LCA, hybrid. Referred to as production method, consumption method and integrated method.
(Mongelli, Sangwon Suh, & Gjal Huppes, 2005)	Review of Methodologies	2 life cycle databases compared.
(Park, 2005)	Review of Methodologies	Material-flow analysis (NEAT) and IPCC reference approach (IPCC-RA)
(Rowley, Lundie, & Peters, 2009)	Review of Methodologies	process analysis vs. I-O analysis and hybrid method
(Wiedmann, 2009)	Review of Methodologies	Multi-regional IO analysis, consumption-based accounting
(Costa, 2000)	Review of Methodologies in the forestry sector	Stock change method, average storage method and ton-year approaches
(Emery, 2003)	Review of carbon auditing Methodologies in the transport sector	Author's own methodology, created from guidelines and review during study.
(Carrington, 2009)	Comparison of free online carbon calculation tools for UK household energy consumers.	UK households free online calculation tools.
(Mathiesen, Münster, & Fruergaard, 2009)	Methods of identifying & using marginal electricity & heat technologies in key LCA studies.	Consequential LCAs
(McKinnon & Piecyk, 2009)	Review of Methodologies	Four approaches used to calculate carbon emissions from UK road freight transport
(Meier, 2002)	LCA of Natural Gas Plant vs. integrated PV cell.	Use of Net Energy Analysis and LCA theory. IO tables and PCA used for energy inputs.
(A. Ciroth, Fleischer, & Steinbach, 2004)	Uncertainties in LCA	ISO LCA

**Table 4.2:** 28 studies considered in reviewing life cycle assessment (2)

Of the 28 studies considered, 1 was considered (Costa 2000) as not contributing to the aims and objectives of this review since it predominantly discusses carbon credits and the nature of carbon storage. 13 were considered to somewhat contribute while 14 were considered to clearly help in developing key characteristics with which to assess current life cycle GHG assessments. It is believed that there is enough current literature to provide a standardised methodology to which historic LCAs and current methodologies can be critically assessed and benchmarked. It is also believed that the current literature shows how methodological choice will affect not only the total carbon emissions calculated but also the usefulness of that methodology in decision-making and meeting the UK emissions reduction targets. The ISO standards for Life Cycle Assessment provide enough guidance to develop a standardised methodology for assessing the life cycle GHG emissions of power supply infrastructure.

A number of the studies refer to the ISO standards in particular. Four studies (Finnveden et al. 2009; Weidema et al. 2009; Reap et al. 2008a; Reap et al. 2008b) form the basis of current understanding of ISO LCA since the most recent standards were published (2006). These papers can be effectively used to critique published LCAs.

There are four phases in an LCA study (ISO 2006a):

1. Goal and scope definition phase,
2. Inventory analysis phase,
3. Impact assessment phase, and
4. Interpretation phase.

In 2008, Reap, Roman, Duncan & Bras published their findings on the unresolved issues throughout the four phases of ISO LCA in two parts. In their words, ISO LCA “*is still in need of improvement*” and there are still numerous problems that can occur throughout the four phases of LCA that “*reduce accuracy of the tool*”. Summarised, these are:

- A. In the first two phases of LCA, functional unit definitions, boundary selection and allocation cause accuracy issues with the methodology. These arise from user interactions with the methodology in their decisions about inclusion and exclusion criteria (cut-off criteria) for processes. Other decisions about the functional unit

being considered, the boundaries of the study and physical relationships between the included processes have a large impact on the value of the LCA (Reap et al. 2008a).

B. In the last two phases of LCA, spatial variation and the local environmental uniqueness inherent in a study created the critical issues in the methodology. These arise from data availability and data quality issues (Reap et al. 2008b). This will be discussed in depth individually later since a number of the studies from this review cite data issues as critical to LCA methodology.

<i>Phase</i>	<i>Problem</i>
Goal and scope definition	Functional unit definition* Boundary Selection* Social and economic impacts* Alternative scenario considerations*
Life cycle inventory analysis	Allocation Negligible contribution ('cut-off') criteria Local technical uniqueness
Life cycle impact assessment	Impact category and methodology selection Spatial variation Local environment uniqueness Dynamics of the environment Time horizons
Life cycle interpretation	Weighting and valuation* Uncertainty in the decision process
All	Data availability and quality

\*Problems can be considered pivotal decisions. Unlike other problems, their partial dependence on study goals limits the capacity to generate solutions via scientific and technical consensus building. However, their strong influence on a study's outcome makes the inaccuracies introduced by an appropriate decision high. It might, therefore, be more appropriate to think of these problems as problematic decisions.

**Table 4.3:** LCA Problems by Phase (Reap et al. 2008a; Table 1)

Table 4.2 presents problems that result in problematic decisions, amongst other problems. Taking the first two phases (goal and scope definition and life cycle inventory analysis) and their associated problems shown above in Table 4.2, proposed solutions are presented in Table 4.3 in relation to wind plants as an example of how life cycle assessment – and specifically here life cycle GHG assessment – within a sector

and for a given technology would be standardised. A review of a recent LCA of a typical wind farm is presented below and suggests solutions to resolving problematic decisions within an LCA of a specific technology (D'Souza et al. 2011).

<i><b>Problematic decision</b></i>	<i><b>Solution for wind power</b></i>
Functional unit definition	1 kWh of electricity delivered to the grid by wind farm operating under medium wind conditions.
Boundary Selection	These are now generally agreed for given technologies. Typical onshore wind farm: (D'Souza et al. 2011; Figure 2, p7)
Social and economic impacts	GHG emissions can be considered the same anywhere in the globe. Economic estimations have been made so that literature can be used.
Alternative scenario considerations	Variation in wind plant lifetime: $\pm$ 4years Variation in frequency of parts replacement End of life credits: impact of recycling on the life cycle
Allocation	There are extensive requirements but they have been summarised within the LCA document. For a full description see D'Souza et al. 2011; Supplement C. One example: Tower; tower shells fabricated and assembled into sections at given factory; allocation rule – kg of tower produced
Cut-off criteria (Negligible contribution criteria)	Number of rules applied for mass, energy, environmental relevance and sum of neglected material flows. For full see D'Souza et al. 2011; Section 3.3. E.g. Mass – if flow is less than 1% of the cumulative mass of all inputs and outputs of the LC impact model, it may be excluded, provided its environmental relevance is not a concern. This should be carefully reviewed since the “environmental relevance” must be clearly defined.
Local Technical Uniqueness	This would be clearly solved by an attributional life cycle assessment of a given project. Care would be taken for ‘typical’ studies where aggregate data could be used. It should be within a standard that local technical issues are assessed and clearly discussed.

**Table 4.4:** Suggestions for resolving problematic decisions in LCA in relation to a specific technology. Information from D'Souza et al. 2011.

Table 4.3 above shows a quick set of suggestions for resolving problematic decisions in an assessment but it should be an example of how – for a given technology – work should be carried out to define solutions for each of the points raised for given

technologies and then in the future, a given sector based on the knowledge gained from each technology. The development of more appropriate guidance to problematic decisions in LCAs of a given technology is presented in the following chapter for wind power.

Reap et al. (2008) “*echo[s] calls for peer-reviewed, standardised LCA inventory and impact databases*” and identified the development model bases as important for addressing problems with data availability and quality.

The two other studies that should be mentioned at this stage come after Reap et al. (2008a and 2008b) and further highlight important areas of LCA that should be reviewed. Both also have a more positive tone. Finnveden et al. (2009) talks of the “better understanding” developing in the approaches of consequential (decision-based analysis) and attributional (analysis of a specific project) LCA studies, referring to the “foundational” user choices and decisions that Reap et al. (2008) discuss. The distinctions between whether the study is consequential or attributional are relevant for the system boundaries, data collection and allocation decisions (Finnveden et al. 2009). Therefore, in relation to this review and Table 4.3, a further column would be added that would give solutions for consequential life cycle assessments. These decisions have important implications on inventory analysis and data availability and quality. Weidema et al. (2009) discusses how these decisions are important for issues of size of the study and time horizons. This study talks about the relative merits of consequential and attributional LCAs for different applications. These are meso, micro and macro scale studies and the main findings from the study are outlined below. As can be seen, a framework for life cycle GHG assessment would need to consider these different levels of scale and their relative characteristics. It should be noted that in this study, project-orientated (micro) systems are the only scale that have a clear need for standardisation.



<i>Level</i>	<i>Main Characteristics</i>	<i>Main Expressed Needs</i>
Micro systems ( <b>project-orientated systems</b> ) with <b>limited modifications/effects on space, market, time etc.</b>	low variability; low complexity; low uncertainty; good knowledge of data and models	standardisation; simplicity; user friendliness; etc.
Meso systems, <b>with relevant effects on other systems and on time and space.</b>	low variability; high complexity; average uncertainty; availability of enough reliable models and data	reliability; prevalence of analytical methods over procedural methods or quantitative vs. qualitative; involvement of stakeholders; rebound effects; sensitivity analysis; etc.
Macro or economy-wide systems, <b>with low reversibility, high penetration and diffusion capacity in all domains and with relevant effects on all levels.</b>	high variability; high complexity; high uncertainty; many lacks of knowledge and data	completeness – all possibilities, interactions and mechanisms considered – involvement of experts; combination of procedural and analytical methods; heuristic approach by improvement of learning systems; “upgrading” system; etc.

**Table 4.5:** Scalar characteristics of LCA studies. Adapted from (Weidema et al. 2009)

In terms of the power sector, large consequential studies would represent macro systems and therefore have the associated issues as outlined above. However, for micro systems such as a nuclear power plant, it is seen that there is already good data and low variability of results compared to other scales. In order to improve the accuracy of the grid intensity factors published; assessment should be conducted on a micro level. Therefore it appears, based on scale, that life cycle assessment and life cycle GHG assessment is already in a state that could improve grid GHG intensity factors with relatively small inaccuracies. Rather than attempting to consider the whole system, a series of micro systems should be considered in order to develop the whole macro system’s characteristics in relation to GHG emissions.

A standard framework “*is very helpful to identify a coherent way to link micro analysis (where it is possible to implement a very detailed model, using the ISO LCA) to the macro level where, indeed, most of the sustainability questions reside*” (Weidema et al. 2009)

The availability of good quality data is considered in the 2009 papers. It is prioritised by Finnveden et al. (2009) that there should be “*development and maintenance*” of databases for use in LCAs especially if the assessment’s results are to be viewed by a number of different disciplines, which is true in the case of the power sector. Data availability is also important for the discussion of hybrid LCA approaches. It is important to define what is meant by a hybrid approach, as explained by Weidema et al. (2009):

*“In the context of LCA and Input Output Analysis, hybrid is used in at least two meanings: hybrid units, that are the combination of physical and monetary units... and hybrid data, that is the combination of process level data and industry level input-output data in the same database.”*

The focus in this chapter is on data. As will be discussed in Section 4.6.2, hybrid data has greater complexity for users of LCA. However, in the context of data availability and data quality, the use of Input-Output tables with LCA enables the assessor to move from a data gap issue that could exist from process-based analysis to a data quality and uncertainty issue at the inventory level (Finnveden et al. 2009). This can only be advantageous for the future development of LCA since a greater understanding will be achieved. It is also shown that the differences in physical data (process-specific information) and economic data (Input-Output Tables) can help to understand different scales of system (Weidema et al. 2009). Weidema also developed a data quality evaluation matrix that is used in LCAs and can provide a good summary for a given LCA or indeed life cycle GHG assessment in relation to its data. This is shown in Section 4.6.3.

To conclude, LCA has become a dominant and influential environmental management tool but it is not without its problems, as shown. What is required now is that lessons learnt allow for focused improvements in LCAs, and life cycle GHG assessments for meeting GHG emissions reduction targets in specific sectors. The following sections

tackle the specific problem areas that this review has found to be most in need of improvements.

#### **4.6.2 Support for a Hybrid Approach to Assessment**

A hybrid approach to assessing the environmental impacts of a product or service utilises both cost-based information and material-based information in the same assessment. A hybrid approach is defined as a “*combination of two otherwise distinct [assessment] approaches*” (Weidema et al. 2009) and the literature mentions that one should be aware that the term hybrid refers to both the units and the data and it should be clearly defined at the beginning of a study as to whether one or both are relevant to describing the methodology used, as already mentioned with regards to attributional and consequential studies. Hybrid units are the combination of physical and monetary units. Hybrid data is the combination of process level data and industry level input-output data in the same database (Weidema et al. 2009). These distinctions should be known in order to correctly track methodological choices. The concept of a hybrid approach to life cycle GHG assessment has been discussed in seven of the studies considered in this review, two of which are also considered conclusive. One paper (Weidema et al. 2009) specifically deals with guidelines of this approach based on work from the CALCAS (EU 6th Framework Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability) project.

Fundamental to this work is the use of the two distinct approaches of life cycle GHG assessment (and life cycle assessment):

- Material-based analysis concerned with physical units (e.g. kg of CO<sub>2</sub> per kg of steel). As will be expanded upon in Section 4.6.3, this type of analysis takes data from the whole life cycle of the specific project being accounted for. As discussed later, this currently results in a number of data gaps.
- Cost-based analysis concerned with monetary units (egg. kg of CO<sub>2</sub> released in the production of one unit worth of value (£)). This type of analysis requires averaged data for the activities and products in the economy of the sector concerned in the study. This is currently collated in Input-Output tables (a term referring to a variety of tables containing monetary information on supply, use, activities and products for a given region). As discussed later, while this data is averaged for whole economies, it is available and so presents an issue of data uncertainty as opposed to data gaps.

Therefore, a hybrid approach to life cycle GHG assessment utilises both of these in order to better account for carbon throughout the life cycle of a system. The literature contains a number of important points on using such an approach and it is important to distinguish between different types of hybrid approach, as outlined in Table 4.5.

Hybrid approaches are considered to add value to life-cycle assessments of systems and impacts better assessed through use of both economical and ecological data (Suh 2004), provided important strengths and weaknesses of the types of hybrid approach are known. This opinion is supported in a number of studies in the review, particularly on selecting system boundaries and choosing inventory data (Suh et al. 2006; Suh & Hupples 2005; Mongelli et al. 2005). It should be noted that these papers all have the same author involved. Two other studies also agree with the above point and suggest that for a relatively small increase in complexity for the study, considerable advantages are achieved. These include a better understanding of the system being assessed (Jiusto 2006) and overcoming the issue of data gaps in process-based LCA, while avoiding such disadvantages of product-based LCA as using aggregated data (Rowley et al. 2009).

There are, however, still a number of issues in using hybrid approaches to LCA and gaps in knowledge of integrating two distinct approaches. These include differences in the time-frames considered since material-based analysis is based on a steady-state whereas cost-based analysis on 1-year accounts as well as other economic information that may be difficult for practitioners to understand without prior knowledge (Weidema et al. 2009).

Key to developing a life cycle GHG assessment standard framework for the electricity sector, hybrid approaches to LCA will fill data gaps and the CALCAS project (Weidema et al. 2009) offers guidelines for the use of incorporating the two distinct approaches of cost and material-based analyses. This is a good starting point for a sector-specific guideline but further research is needed from this review in order to ensure that the CALCAS guidelines add value to the assessment approach for the electricity sector.

Table 4.5 presents three different hybrid approaches and highlights how the choice of hybrid approach may result in different strengths or weaknesses for an assessment. It

can be seen that weaknesses exist with all approaches, but hybrid assessment using economic input-output based data have the largest number and may not represent the system in question as well as tiered or integrated hybrid approaches. This information on relative strengths and weaknesses of approach will be considered in conducting a hybrid life cycle assessment in Chapter 6 of this thesis.

<i>Approach</i>	<i>Strengths</i>	<i>Weaknesses</i>
Tiered hybrid	Easy to use	Problem with double counting
	Literatures, databases and case studies well documented	Recurring flows by process-flow diagram approach
Input-output based hybrid	Avoid double counting	Use and end-of-life phase are externally added to the main system
	Process part and input-output part are described in a consistent framework	Recurring flows between the main system and use and end-of-life phase are not properly described
		Should be combined with other methods if the national economy is highly dependant upon imports
Integrated hybrid	Consistent mathematical framework for the whole life-cycle	Relatively complex to use
	Avoid double counting	High data and time requirements
	Easy to apply analytical tools	

**Table 4.6:** Comparison between hybrid approaches as assessed by Suh et al., (2006)

One such solution is offered as to how to decide when to use which approach:

*“In a tiered hybrid analysis, the direct and downstream requirements (e.g., construction, use, maintenance, and end-of-life) and some important lower order upstream requirements of the product system under study are examined in a detailed process analysis while remaining higher order requirements (e.g., materials extraction and manufacturing of raw materials) are covered by input-output analysis.”* (Suh et al. 2006)

A key issue requiring further understanding is how hybrid approaches will work in practise. It has been shown from the literature that it is has been long known that hybrid

approaches provide a more complete accounting process. However, it is still not the case that industry is using this approach. The reasons behind this will be further explored in the following chapters 5 and 6. Weaknesses such as time and high data requirements and model complexity suggest reasons for the lack of support for these more complete accounting approaches. Model sophistication is also considered in the following section since the method of approach influences exposure to uncertainty in accounting (section 4.6.4).

#### ***4.6.3 The importance of good quality data availability***

Amongst the 28 studies that were considered, six examined the importance of data availability and quality, of which one is considered conclusive by this review in relation to its aims and objectives (Reap et al. 2008b), while five offer partly-conclusive comments in support of the following discussion. The conclusive study is part of the most recent review of the LCA framework and identifies data availability and data quality as a critical problem in LCA.

Reap et al. (2008b) clearly identify the need for databases, as they are integral to a standardised framework and should be regularly monitored and developed. A standardised life cycle GHG assessment framework would fail without such an open and dynamic database. It also supports the need for hybrid data (process databases and environmentally extended Input-Output tables) to be made available in order to remove the risk of accounting being exposed to uncertainty and potentially data gaps. The opinions given by the authors are also supported by Wiedmann, (2009) in that data availability and quality is critical to LCA.

Table 4.6 shows the evaluation matrix that was developed in order to rank data (Weidema 1998). While it does not provide any statistical measurement of data variation, it does go some way to improving awareness of where data comes from and how it may be improved. Table 4.7 shows an example of this table in use in an LCA of a typical wind farm (D'Souza et al. 2011). It is therefore recommended that this become standard in all life cycle GHG assessments, as well as larger LCAs as a minimum for presenting data origins.

Indicator score	1	2	3	4	5
<b>Indicators, which are independent of the study in which the data are applied:</b>					
Reliability of the source	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate or unknown origin
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
<b>Indicators relating to the technological and natural production conditions under which the data are valid, and therefore dependent of the data quality goals for the study in which the data are applied:</b>					
Temporal correlation	Less than 3 years of difference to year of study	Less than 6 years of difference	Less than 10 years of difference	Less than 15 years of difference	Age of data unknown or more than 15 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but from same technology	Unknown technology or data on related processes or materials, but from different technology

**Table 4.7:** Data Quality Matrix (Weidema 1998)

<i>Type of Data</i>	<i>Reliability of source</i>	<i>Representativeness / Completeness</i>	<i>Temporal Correlation</i>	<i>Geographical correlation</i>	<i>Further technological correlation</i>
Manufactured components	2	1	1	2	1
Manufacturing process	1	1	1	1	1
Large purchased components	2	1	2	3	1
Small purchased components	2	1	2	3	2
Site preparation	2	1	1	3	2
End of life	3	1	2	3	1

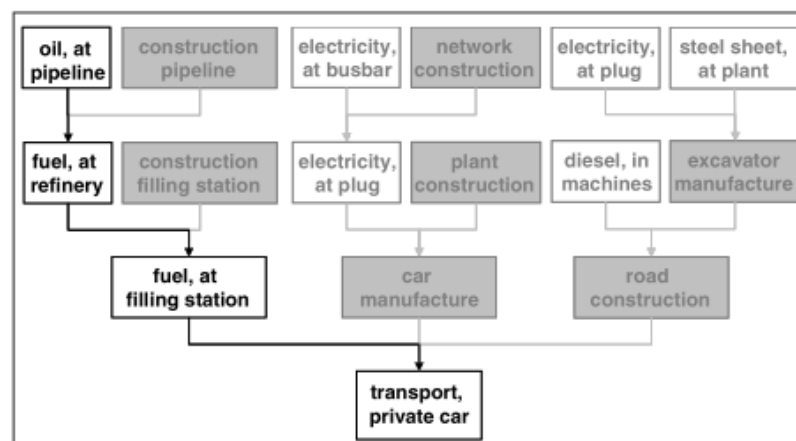
**Table 4.8:** Data Quality matrix in the context of a typical wind farm (D'Souza et al. 2011)

The two tables above help to evaluate data quality in terms of its origins and allow for improvement of data and indeed the definition of good data in a number of areas, such as the age of the data and the location origin of the data. This should be deployed as standard in future life cycle assessments and life cycle GHG assessments.

Finnveden et al., (2009) supports these comments in their editorial, stating that data choice is also dependent upon the goal of the LCA and the choices made should be clearly identified. This will be discussed further in section 4.6.5 but refers to whether an

LCA is attributional (on a specific project) or consequential (studying the effects of a decision). The editorial comments by Finnveden (2008) also say that marginal data (proposed data as a result of change to a process/system) should be used in different scenarios for consequential LCAs. In other words, the data should reflect solely the scope of the study. It is also stated in the editorial, however, that this is not as simple as it sounds.

Hybrid LCAs and those using cost-based data utilise aggregated data for whole systems through their use of environmentally extended input-output data. One study (Mongelli et al. 2005) reviews two inventory databases from the US and Europe - one cost-based and one process-based. They conclude that process databases give smaller contributions for some sectors, and specifically capital goods, especially in the global warming potential impact category. They identify systematic truncation as a possible reason for this consistent difference between the two different approaches. This is the cutting off of processes in a system perceived to be non-consequential or insignificant to the particular value for the given system. Figure 4.1 is an example of how choices made by the assessor create truncation errors. While this is an assessor choice (expanded upon in section 4.6.5) it does help explain truncation.

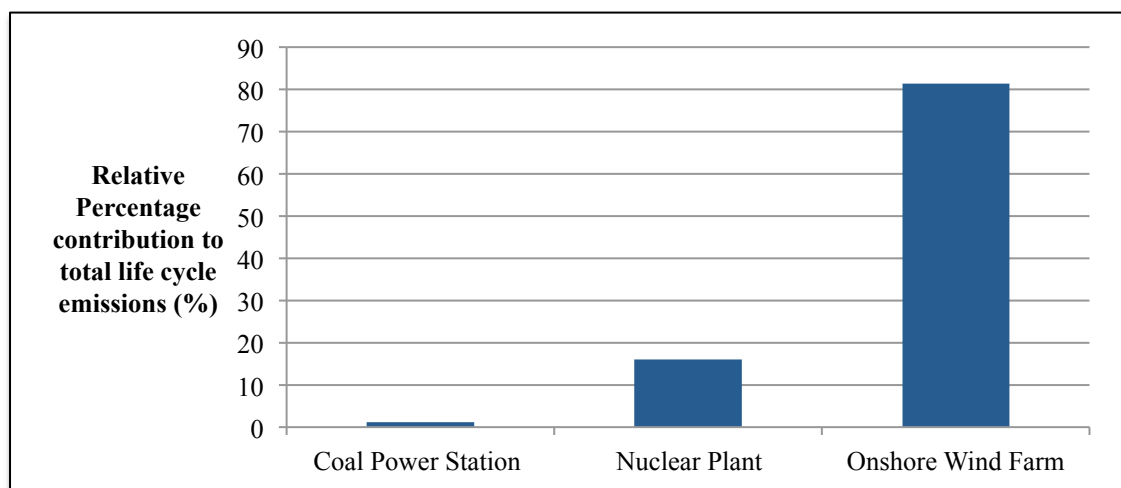


**Figure 4.1:** The dangers of simplifying a product system. Example is transport service provision by private car taken from Frischknecht et al., (2007) and the truncation is exclusion of capital goods from this LCA (those greyed out). Only the black unit processes are considered.

Frischknecht et al. (2007) presents a detailed paper on the inclusion or exclusion of capital goods in a life cycle assessment in relation to the Centre of Environmental



Science, Netherlands (CML) baseline characterisation factors: of the impact categories of global warming, acidification, eutrophication, human toxicity, fresh-water aquatic toxicity, terrestrial ecotoxicity, ionising radiation, and land competition, based on proxy indicators (fossil and nuclear) cumulative energy demand, and based on the end-point indicators Eco-indicator 99 (H,A) mineral resources, human health, eco system quality and totals. What is important in this instance is that by using one approach, there is clear incompleteness in the LCA (or some measurable uncertainty). The study also mentions that wind and PV-based electricity are “very much or even completely affected by capital goods contributions” in all of the impact categories, as shown below. This means that reliable data should be available for all processes through the life cycle of emerging renewables in order to ensure that these contributions are not neglected. Any life cycle GHG assessment standard for electricity production would depend upon capturing appropriate data for capital goods in particular. This is critical if the UK electricity supply mix is to have considerable contributions from renewables since their life cycle emissions characteristics are clearly different to traditional power plant. This can be seen in Figure 4.2 in a comparison of Wind, Nuclear and Coal with respect to their differences in the contribution of construction, manufacture and decommissioning with respect to their total life-cycle emissions.



**Figure 4.2:** Comparison of the contribution of construction, manufacturing and decommissioning to total life –cycle emissions for three generation technologies. Sources: Coal - (Odeh & Cockerill 2008), Nuclear - (British Energy 2005), Wind - (D’Souza et al. 2011)

In conclusion to this section, it is seen that the literature emphasises the need for accurate data to be available in order to proceed with developing a standardised

framework for life cycle GHG assessment of UK electricity supply infrastructure. Indeed, such databases now exist in Europe (Ecoinvent) and it is up to practitioners to further develop these databases and critically assess the quality of the data within them. However, it is still not agreed that only this or any other database should be used. It is also required that Ecoinvent is purchased at present which may be a barrier to such databases becoming standard. National databases may need to be produced by third parties with no vested interest. This section also highlights issues with different data being used in different studies, depending on the goals and scope of the study. Such user choice will be discussed in section 4.6.5, but this appears to be an issue of agreement and standardisation could resolve this. In other words, it could be specified that marginal data could always be used for consequential LCAs and specific data for attributional LCAs for example. This will require further research, preferably at a micro level.

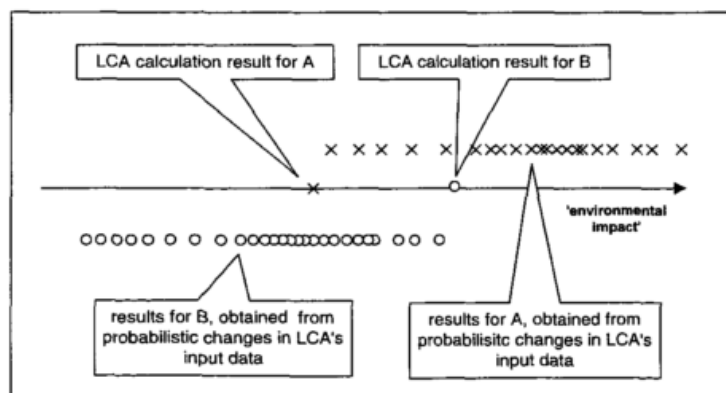
Finally, the issue of variability versus uncertainty should be acknowledged as important for inventory development and databases more generally. Variability offers the decision-maker some idea of the probable difference between LCA results and the real situation. Uncertainty presents a much larger risk to decision-makers since it suggests a gap in the data. This will be expanded upon in the next section. Wiedmann, (2009) suggests that these uncertainties (referring to both variable data and uncertain data in multi-regional input-output datasets) are still outweighed by the potential benefits of understanding international trade and technologies. This could be measured statistically in order to support this claim but philosophically, it does seem reasonable that as understanding increases of the data sets and their development, understanding of those systems will be greatly improved.

#### ***4.6.4 Importance of showing uncertainty in life cycle carbon assessments***

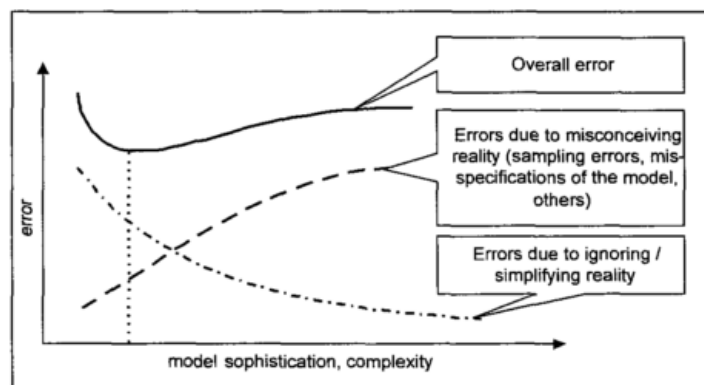
Amongst the 27 studies, two examined how uncertainty specifically is presented in LCA currently (Heijungs & Huijbregts 2004; Lloyd & Ries 2007) and one study suggests a method for calculating uncertainties in LCA (Ciroth et al. 2004). All three of these studies are considered conclusive by this review. Uncertainties here describes how “measured values frequently do not match the true values, but differ from them in a probabilistic manner” (Ciroth et al. 2004). It should be mentioned that this is not the definition for uncertainty as defined by (Finnveden et al. 2009) but rather refers to the broader concept of uncertainties. Where data gaps exist (i.e. an uncertainty) some

judgement will be made on what data to use in the gap and this will have variability on the real figure, based on the characteristics and origins of that data. This is another example of where further definition of key concepts should be made through standardisation. The ability to describe how an assessment has managed to capture the “true” detail is critical if decision-makers are to make an informed choice. It should be recognised that no measurement is devoid of this error or difference between the true and the measured value (Ciroth et al. 2004) but getting as close as possible is the main goal of any environmental management tool.

The literature shows that the movement of uncertainty through an LCA must be better understood, since it can arise in different forms throughout the assessment process. This is important in understanding the relationship between model sophistication and model uncertainty. It is best described in the figures 4.3 and 4.4.



**Figure 4.3:** The comparison between two products with respect to their range of results, based on their variable data (Ciroth 2004)



**Figure 4.4:** The relationship between model error and model sophistication (Ciroth 2004)

This shows in general form how “*an optimum for model sophistication is not always a highly sophisticated model*” (Ciroth 2004). Measuring such a statement would help significantly to determine a standardised framework for life cycle GHG assessment based on LCA principles. It can be seen that raising the complexity of an assessment approach will raise the overall error and so may suggest simpler is better for most assessments. The vertical dotted line suggests some optimum solution where complexity is minimised for overall error - the critical point that should be reached by a standardised framework for life cycle GHG assessment.

An important distinction should be made when discussing LCA errors between variability and uncertainty. This is also given in the Definitions section (4.4.3) at the start of this chapter.

1. **Uncertainty** relates to a lack of knowledge: no data or that data available is either wrong or ambiguous.
2. **Variability** in contrast describes data that is of a homogeneous nature. This type of data is also called averaged data by LCA practitioners (Finnveden et al. 2009).

Heijungs & Huijbregts (2004) commented on previous research into classifying uncertainty in data and further attempt to classify it by the following descriptors:

- **Spread** - for data for which more than one value is available;
- **Assessment** - for data for which an inappropriate value is available;
- **Pedigree** - for data for which no value is available.

These descriptors should be known and understood for standardising life cycle GHG assessment and another example of the requirement of having standard definitions.

In relation to the two distinct approaches of life cycle assessment, as outlined in the previous section (4.6.2), it can be said that material-based analysis is more commonly affected by data uncertainty in that data gaps are more common with this approach due to reliance on process-based data which may not be available for a specific study (Finnveden et al. 2009). However, it may be available and in which case will relate to variable results and so some probable distribution should be known for that data.

Material-based analysis may offer less uncertainty, but more variability due to the use of aggregated data in a study that may be for a specific site. LCAs and life cycle GHG assessments should also include different scenarios in order to protect from variability in data from assuming only one scenario.

Table 4.8 clearly shows how numerous sources of uncertainties exist within the LCA framework. Parameter (input data) uncertainty could be reduced in developing a standard database for a specific sector or technology, as well as model uncertainty being reduced in standardising the life cycle GHG assessment methodology. Scenario uncertainty may be more difficult since it is more heavily dependent on the goal and scope of the study, but on discussing the differences between attributional and consequential LCAs, there appears to be some suggestions that can be made from the literature that begin to propose data choices and transparency through formalising the assessment methodology.

<i>Sources of uncertainty and variability</i>	<i>LCA Modelling component</i>		
	<i>Parameter (input data)</i>	<i>Scenario (nominative choices)</i>	<i>Model (mathematical relationships)</i>
Random error and statistical variation	Parametric measurement error	Imperfect fit of data to regression for evaluating trends and forecasting	Measurement error in physical constraints or modelled relationships
Systematic error and subjective judgement	Methods for estimating missing data	Developing scenarios based on past trends, using value judgement	Extrapolating relationships from well-studied processes to similar processes
Linguistic imprecision	Assigning quantitative parameter estimates based on qualitative descriptors	Developing scenarios based on qualitative descriptions	Building models based on qualitative descriptors of relationships
Variability	Inherent geographical, temporal, and technological variability in parameter data	Inherent variability in scenario characteristics	Inherent variability in process relationships
Inherent randomness and unpredictability Expert uncertainty and disagreement	Simplification of fluctuations in measured variables A single parameter value is not widely accepted	A scenario in which simplified characteristics are used Estimates of scenario characteristics	Inconsistent process characteristics Disagreement about process mechanisms and system behaviour
Approximation	Characterising parameters by a few important properties	Choice of functional unit, allocation rules, system boundaries, cut-off criteria	Simplifications of real-world systems, such as system boundaries

**Table 4.9:** Example Sources of Variability and Uncertainty in life-cycle assessment. (Lloyd & Ries, 2007; Table 1)

One paper suggested further areas that need research, beyond the outlined uncertainties above. These should also be known in an attempt to improve the environmental management tools used:

*“The model uncertainty is much less addressed. And the more profound forms of uncertainty, for instance epistemic uncertainty may fundamentally be difficult to deal with.”* (Heijungs & Huijbregts 2004)

Epistemic uncertainty can also be referred to as systematic uncertainty and can be defined as uncertainty arising from a lack of knowledge or understanding and in this instance can relate to the assumptions made by the assessor. Table 4.9 summarises methods of dealing with uncertainty throughout the LCA framework and measuring it in some way.

<i>Method of processing uncertainty in LCA</i>	<i>Where uncertainty arises</i>		
	<b>Input</b>	<b>Processing</b>	<b>Output</b>
<b>Parameter variation/scenario analysis</b>	<p>Parameter variation - number of different values available for one or more parameters. Treating all parameters individually may lead to large number of scenarios. Therefore, usual to vary one parameter and keep all other parameters fixed at some “most probable value”, and to repeat procedure for all parameters in separate analysis. Alternative is to define a limited number of scenarios with specific but consistent realisations of each parameter.</p>	<p>Different data sets and/or models and/or choices investigated as to their consequences for model results e.g. Results calculated for data set with high emission values and low emissions values</p>	<p>At the output side there are fewer differences. In combination of parameter variation, one often sees the consecutive presentation of tables and/or graphs for the different sets of parameters or scenarios</p>
<b>Sampling method</b>	<p>Sampling methods are based on the random variation of uncertain parameters. They require the specification of a statistical distribution of every stochastic parameter. Frequently encountered distributions are: the normal distribution; the lognormal distribution; the uniform distribution; the triangular distribution. These distributions may or may not be correlated across parameters. In principle, correlations between parameters may be expressed by a correlation matrix or a covariance matrix. Apart from correlations between input parameters, correlations between model outputs should be accounted for in comparative LCAs. This can be done in the form of a comparison index for the case of two alternatives, or in a more general discernibility analysis.</p>	<p>Computational repeating of calculations many times. For input data from some distribution, results differ from run to run. This gives rise to a sample of results and the statistical properties can be investigated. Monte Carlo Analysis is the most well known method of doing this. This method can be used for scenarios. Would consist of combinations of different decision scenarios and model formations with subjective probability reflecting preferences of decision-maker or faith of modeller in particular model formation for the alternative scenarios. According to the paper this table is based on, the output reflects uncertainty of decision-maker regarding normative choices involved (scenario uncertainty) or uncertainty of modeller regarding the alternative model formulations (model uncertainty)</p>	<p>Results of sampling methods can be presented in different forms. Sampled probability density plots, so-called histograms, are a typical example. An alternative is the graphical representation of an average value with two boundary values. These boundary values may indicate the smallest and largest value obtained, or a more robust measure such as the 5 and 95 percentile values.</p>

**Table 4.10:** Methods of dealing with uncertainty in LCA. Detail from (Heijungs & Huijbregts 2004) and put in tabular format. (1)

<i>Method of processing uncertainty in LCA</i>	<i>Where uncertainty arises</i>		
	<b>Input</b>	<b>Processing</b>	<b>Output</b>
<b>Analytical method</b>	<p>These are based on the estimation of the moments of the distributions. In particular the second moment, the variance, is used in a first order Taylor approximation. Thus, not the distribution, but only the variance (or standard deviation) of the parameter is needed here. Thus, less information is needed for analytical methods than for sampling methods. Like for Monte Carlo analysis, correlations between varieties can in principle be included, although this is seldom seen in practice. Inclusion of correlations in the analytical case implies a broadening of the scope to second-order Taylor approximations.</p>	<p>Involves explicit mathematical expressions for distribution of model results. Their use is based on first order approximations of the Taylor Expansion of the underlying model. Distribution-free variances of input parameters can then be used to calculate variances of output variables. Use in LCA is limited so far; the mathematics is complex for software.</p>	<p>Analytical methods do not provide a distribution of outcomes. Instead, they provide moments of the distributions, such as the standard deviation. These can be used to calculate and visualise 95% confidence intervals. As analytical methods have hardly been applied in LCA, we cannot give an example of its use.</p>
<b>Non-traditional Methods</b>	<p>Because methods for processing uncertainties on the basis of non-traditional methods have hardly been applied in LCA, it is not clear which types of input information would be needed.</p>	<p>Not part of traditional statistics curriculum. Comprises a variety of methods, e.g.: fuzzy set methods; Bayesian methods; non-parametric statistics; robust statistics; neural networks and other methods from artificial intelligence. Methods for uncertainty analysis based on fuzzy sets have been introduced into LCA by several authors. Bayesian statistics has not been mentioned in the context of LCA, except on one occasion. The other mentioned methods are even less used within LCA, although the sign test and the Kruskal-Wallis test are briefly touched.</p>	<p>The above information on output uncertainty for analytical methods holds even truer for the non-traditional methods, like fuzzy sets methods and Bayesian methods.</p>

**Table 4.11:** Methods of dealing with uncertainty in LCA. Detail from (Heijungs & Huijbregts 2004) and put in tabular format. (2)



Table 4.9 summarises methods of dealing with uncertainty throughout the LCA framework and measuring it in some way, although three of four of these may become complex to non-practitioners of LCA since they require statistical modelling. This is another area where complexity needs to be weighed up with acceptable error. This is not to say that continuous improvement should not be made, but a standard may need to develop around different stakeholder needs. This is also commented on:

*“The fundamental problem is a trade-off between two aspirations. The first is the (idealistic) motivation to utilise as much available information (qualitative or quantitative) about uncertainty—and as few unwarranted assumptions about that information—as possible. The conflicting aspiration is to factor all uncertainty models, however heterogeneous in form, into an efficient, rational decision-making process. To date, there are no frameworks for uncertainty analysis in LCA that guide characterization of this trade-off to make the assessment as comprehensive as possible yet still tractable in terms of decision making.”* (Reap et al. 2008b)

These comments come a while after the Weidema (1998) Data Quality Evaluation Matrix, suggesting that practitioners of LCA still require more statistical methods for evaluating uncertainty, as opposed to Weidema’s qualitative scale. However, there may be some ground between the two in order to meet this ideal situation of complexity balanced with error. This will not be known, however, without further research specifically on uncertainties in LCA and other environmental management tools.

Reap et al. (2008b) comment on this in the context of cut-off criteria imposed by the user:

*“The criteria used to identify and eliminate (“cut-off”) unimportant resource and waste flows become problematic when one attempts to balance information costs against the potential of missing substantial environmental effects. Local technical uniqueness becomes problematic when average or generic data or models are used to represent processes that significantly differ from the norm... Truncations and assumptions about global homogeneity and steady-state conditions introduce the most severe errors in impact assessment.”*

This comment also goes against over-standardisation of life cycle GHG assessment if it prevents accurate reporting of a unique project. It effectively warns against using average data when possible and not to assume homogeneity in assessments. These comments could also be in the following section with regards to the user's choice during assessment.

To conclude, work should be carried out on current methods of presenting uncertainty in LCAs and life cycle GHG assessments of power infrastructure in order to better understand current practice and stakeholder awareness. As with other suggestions, this would allow for a standardisation that could improve uncertainty and variation presentation and accuracy while presenting in a manner that is not alien to the sector at present.

#### ***4.6.5 The role of the user in life cycle carbon assessments***

Amongst the 28 studies, seven examined how the decisions made by the assessor throughout the LCA process affected results. Of these, four were considered conclusive. While it may seem intuitive that the user's subjectivity has an effect on LCAs, a number of distinct issues were raised in the literature. While some of these points have been raised already in this review, it is important to distinguish user choice as a key affecter of results. Standardisation may play the most influential role in this instance. Seven papers discussed the difference between conducting an attributional or consequential LCA. Finnveden (2008) discussed issues of data choice specifically when considering either attributional or consequential LCAs in an editorial and this theme is common throughout the literature. The editorial also suggests that consequential LCAs should develop two or more scenarios through the use of marginal data. It is also emphasised that more knowledge is required on the effects of marginal data on life cycle GHG assessment results since the literature is currently limited.

The following table gives some suggestions for the types of LCA (and so life cycle GHG assessment) that can be used at different scales. This further develops ideas presented in Table 4.4 that outlines some characteristics of different system scales under consideration. Table 4.10 clearly suggests different methodological approaches to the different scales.

<i>Economic size</i>	<i>LCI Model</i>	<i>Examples and remarks</i>
Small	Attributional	Support for day-to-day consumer decisions Make sure that the object of investigation and the decision at issue is not part of a policy measure of public authorities or companies with larger consequences
Medium	Decisional/ attributional in a sensitivity analysis	Strategic decisions of large companies or industry associations Large-scale promotion activities of companies
Large	Consequential/ decisional in a sensitivity analysis	Policy measures on the level of nations, regions or multinational companies Decisional if consequential information and data are missing

**Table 4.12:** Classification of the economic size of the object of investigation and recommended LCI models (Frischknecht & Stucki, 2010; Table 4)

Lund et al. (2010) use consequential LCA in order to examine changes in the electricity mix in Denmark. Some important concepts are identified regarding long-term changes to power plant capacities – an important aspect for future policy. The paper suggests that current LCA standards (or “state of the art” method as called by the authors) do not consider adequately the effects of changes to the electricity mix. The authors suggest that marginal capacity (long term changes to power plant capacities) must be considered alongside marginal supply (the changes in production given the combination of power plants and their individual marginal production costs). This is because these technology changes result in different supply characteristics not only on the average grid carbon intensity, but also on hourly abilities for marginal capacity to meet demand. This is due to the nature of certain new technologies entering the electricity mix being intermittent and hence unable to react to demand changes. The authors suggest that Energy System Analysis (ESA) simulation may be a way to identify the cause and effect nature of both changes in capacity and changes in demand. This will be of vital importance if life cycle GHG assessment is to improve future capacity decisions and demand side management. This chapter therefore suggests that previous consequential LCAs have not adequately been able to model real characteristics resulting from marginal capacity (changes in power plant capacities).

As mentioned previously, Finnveden et al. (2009) talks of the “*better understanding*” developing in the approaches of consequential and attributional LCA studies, referring to the “*foundational*” user choices and decisions that Reap et al. (2008a) refer to. The distinctions between whether the study is consequential or attributional are relevant for the system boundaries, data collection and allocation decisions (Finnveden et al. 2009).

These decisions then have important implications on inventory analysis and data availability and quality. Weidema et al. (2009) discusses how these decisions are important for issues of size of the study and time horizons. This study talks about the relative merits of consequential and attributional LCAs for different applications, relating to scale especially.

To conclude, while this section may be an obvious discussion, it does also support the idea of creating a standard life cycle GHG assessment framework. This framework must also demand transparent decision-making through ensuring that any decision taken by the user is recorded and justified. The warnings against over-simplification and use of average data also highlight a need for project-specific characteristics within an assessment that a standard must be able to accommodate for.

#### ***4.6.6 Role of a standardised approach to life cycle carbon assessments***

Specific information comes from this literature review with regards to comments on what a life cycle GHG assessment standard should include. These are outlined below and are considered of key importance to the development of a life cycle GHG assessment methodology for the electricity supply sector. Many of the problems may simply be in user choice. By applying to a sector, these choices can be made for the methodology. Viewing LCA in all its applications can provide a picture that is vast in its requirements and its uncertainties. However, it is being shown that when applying over a micro-scale, a number of problems can be removed and paths to further reductions can be planned.

Heijungs and Huijbregts (2004) strongly support standardisation in their context of data and uncertainties:

*“The three requirements for becoming a standard procedure, availability of data of input uncertainties, availability of methods and software for processing uncertainties, and availability of methods for interpreting and visualizing output uncertainties, start to be satisfied...The ISO-standards for LCA have canonized parts of the terminology used. On top of that, [other research projects have provided] a standard for data exchange. But especially for uncertainty, clear standards are lacking.” (Heijungs & Huijbregts 2004).*

Also discussed are the issues of nomenclature involved with uncertainty analysis. This is also even said to be the case in the statistics community as much as LCA community. This would be relieved with standardisation.

An example where current GHG emissions calculation tools result in different results is offered by Carrington (2009) in a thesis clearly showing the effects of choosing different available tools to conduct personal carbon accounts. While this isn't relevant directly to electricity supply, it does highlight the need for consistency in life cycle GHG assessment and better direction from practitioners in order to choose the most suitable environmental management tools for the goal of a study. The thesis also shows that applicability of the tools varies largely and so this suggests that any life cycle GHG assessment standard for the power sector must be applicable as well as appropriate, as discussed previously with regards to complexity versus error in LCAs. When dealing with the variety of stakeholders that the power sector contains, it is important to meet the desires of all of them in order to ensure a life cycle GHG assessment tool that will lead to real change. Alternatively, a standard would require different levels of complexity for different stakeholders. In order to use life cycle GHG assessment to improve projects from a design perspective also requires a continued improvement of data quality through the presentation of uncertainties.

There is also a reminder that caution must be taken when standardising assessment tools:

*“Selecting environmental impact categories effectively truncates the types of damages a study considers, thereby introducing inaccuracies. Setting arbitrary time horizons skews results in favour of short- or long-term impacts.”* (Reap et al. 2008b)

This comment argues against only looking at life cycle GHG assessment. Therefore it must always be known that this whole procedure is only one method of environmental management and all other impacts must be considered in the course of a project, especially those at the level of national infrastructure. Over-emphasis should not be put on GHG emissions if other environmental impacts are greater. This must also be a driver for policy in that it should not skew research towards only one or a couple of environmental issues, while others are neglected.

## 4.7 Conclusions

The following specific research questions were addressed in this review:

1. Can common problems in life cycle assessment be outlined in order to remove them in relation to a specific sector and its activities?
2. Can historic LCAs be critiqued in relation to a defined set of key characteristics (resulting from a highlighting of the problems in LCA) of the Life Cycle Assessment framework?
3. Can an improved standard framework be outlined for electricity supply technologies currently in operation or scheduled to contribute to UK electricity generation in the near future?

It should be noted that LCA and life cycle GHG assessment are not the only solutions to reducing national and global GHG emissions. However, as said by Reap et al. (2008b) *“if one accepts sustainability as the ultimate goal, the importance of improving LCA to the point where it offers more than ambiguous directional information is clear.”*

It has been shown that the development of LCA has led to acknowledgement of a number of common problems within the framework that can be discussed and reduced in relation to specific scales and technologies within a sector. The goal of using this set of common problems to critique historic LCAs and life cycle GHG assessments seems reasonable, especially since fewest problems tend to lie at the micro scale. Where larger problems still exist is in larger, macro studies and hence a bottom-up approach to assessment should be the optimum solution, before making decisions on large, macro studies. Similar problems are felt in transport as with electricity generation sector. *“By focusing on a specific sector, guidance can be translated into a useable protocol for transport intensive organisations”* (McKinnon & Piecyk 2009).

**Based on this chapter’s review, historic life cycle GHG assessments should be assessed by:**

1. The system boundaries used. These have been outlined as covering all unit processes in a product/service’s lifespan. Boundaries are to be defined for each generation technology from future research. This is achievable through review of current boundaries chosen in the sector. Agreement on this should be done as soon as possible.
2. The purpose of the LCA is clearly outlined from the outset of the study.

- a. This includes the functional unit of the environmental impact being covered, in this case gCO<sub>2</sub>e/kWh
  - b. Whether the study is attributional or consequential (is it simply calculating life cycle GHG emissions or is it based on a choice or decision)
3. The study uses a hybrid of process analysis and Input-Output analysis if possible. This also applies to the choice of data where gaps exist in process-based data. Economic data should only be used in place of gaps in data availability.
4. Assumptions are clearly presented. Cut-off criteria clearly defined.
5. All data sources are shown.
6. The life cycle GHG emissions are clearly presented and can be compared with other life cycle assessments throughout the lifespan. This is to ensure that the assessment is useful in the technological context.
7. Whether the study contains sensitivity analysis and the type of analysis conducted. This has been outlined as being crucial to understanding any uncertainty in the studies as well as an appreciation of the subjective choices made in the case of consequential LCAs. Further work should be done on this in reviewing current practice and stakeholder requirements and expectations.
8. Use of an internationally available inventory (or combination of inventories, based on goal and scope requirements). So far, Ecoinvent has been suggested as the most up-to-date and widely used LCA inventory.

These key criteria roughly agree with the World Resources Institute/World Business Council's "5 Principles" for carbon accounting in an economy: **Relevance, Completeness, Consistency, Transparency** and **Accuracy**. They also, however, expand on these and are sector specific which is crucial for the sort of step change that economies require under the Climate Change Act and other comparable international legislation.

A review such as the one presented in this chapter will help to determine best practice for each technology in the power sector and lead to more accurate, transparent emissions data for each over the course of their life cycles. This will in turn lead to a more efficient progression to a low-carbon economy. An example of this from literature is the concept of dynamic LCA, whereby the timing of emissions is considered as well as their locations.

*If carbon mitigation is to be accomplished as efficiently as possible [dynamic LCA that considers geographical locations] must begin to be considered in both production and deployment of alternative energy technologies.” (Kenny et al. 2010)*

*“Cross-border co-operation resulting from dynamic LCAs would lead to better global solutions to reducing GHG emissions. This could mean that countries with low carbon intensity grids could promote themselves for manufacture if they have low grid GHG intensity factors. Countries with high factors would also become attractive for mitigation projects due to the increased advantages of introducing marginal technologies. (Reap et al. 2008b).*

These idealistic comments may improve the focus on LCA results and cause the methodological concepts discussed to be further debated. However, none of this is possible without a dramatic change in either the price of fossil fuels directly or a carbon-trading (or similar) scheme that effectively puts an additional cost on those fuels and indeed products that are carbon intensive.

#### **4.8 Suggestions for further research**

1. Further definition of key terms should be made through standardisation of a specific technology and to be followed by the sector. This refers to Tables 4.2 and 4.3 above where functional unit, boundaries and standard scenarios can be defined for a basic, standardised LCA of wind power.
2. Areas out with the above point should be reviewed such as cut off criteria for specific technologies referring to where assessment ceases to consider possible associated emissions out with boundaries. Local technical uniqueness also requires further research and this is assessed in Chapter 6 whereby historic LCAs are reviewed in order to attempt to remove local uniqueness impacts. Allocation such as possible interactions with other technologies requires further research. This is considered in Chapter 7 where wind power interacts with gas thermal plant on an electricity supply network such as that in the UK.



3. Data availability and quality requires continuous review as occurs with the Ecoinvent database. A matrix such as that outlined above (Tables 4.6 and 4.7) should be developed for each technology in order to highlight each assessment's data quality.
4. Databases that are most appropriate for a given sector must be outlined and any gaps should be filled as quickly as possible or a reasonable range suggested through use of economic data in the form of hybrid assessment. They should be reviewed regularly. A novel hybrid assessment will be used in Chapter 6 and further research into each technology's costs in relation to use in hybrid LCA will improve the quality of this data provided accurate costs are known and are made available.
5. A review into specifying types of data for consequential LCAs and specific data for attributional LCAs of projects within the power sector should be conducted. This will require research at a micro level.
6. Echo calls from Wiedmann (2009), suggesting that these uncertainties (referring to both variable data and uncertain data in multi-regional input-output datasets) are still outweighed by the potential benefits of understanding international trade and technologies. This could be measured statistically in order to support this claim.
7. Research into the optimum solution where complexity is minimised for overall error should be carried out. This is the critical point that should be reached by a standardised framework for life cycle GHG assessment. This is because a standard will have to develop around stakeholder needs.
8. Further work should be carried out on current methods of presenting uncertainty in LCAs and life cycle GHG assessments of power infrastructure in order to better understand current practice and stakeholder awareness. As with other suggestions, this would allow for a standardisation that could improve uncertainty and variation presentation and accuracy while presenting in a manner that is not alien to the sector at present.

9. Life cycle GHG assessment should include some time aspect and further work should be done on how this may affect the mitigation potential of each technology. This will only come once a life cycle GHG assessment standard is in place.

The lessons learned from this chapter are important for developing an effective methodology for estimating total life cycle GHG emissions.

Chapter 5 will look at a technology-specific methodology and what critical factors affect the overall estimates for total associated life cycle GHG emissions. Chapter 6 will then use both this chapter's general lessons and those lessons learned from Chapter 5 to develop a methodology most suited for wind farms and specifically offshore wind farms.

A novel hybrid methodology will be developed from the two standard attributional approaches of process-based and cost-based analysis, as discussed in this chapter, which will also be presented for the case study in Chapter 6.

## **Chapter 5 – Valuing GHG Emissions from Wind Power**

This chapter builds on Chapter 4's coverage of LCA as a whole by conducting a statistical review (META-Analysis) of a large number of historic life cycle GHG estimates that are available. In order to develop transparent, consistent estimates, lessons must be learned from historic work based upon current technologies, such as wind power. Wind power has been chosen due to its place in European GHG reduction policy and also that it is the most commercially advanced renewable technology to date. The growth in both onshore and offshore wind power has been rapid over the past few decades and has led to a need for comparable, consistent and reliable life cycle carbon assessment of wind power in order to provide decision-makers with robust information. The current published estimates for wind power range from 2 to 81gCO<sub>2</sub>e/kWh. This study reduces this range through a meta-analysis of 82 estimates gathered from 17 independent studies. Through harmonisation of lifetime, capacity factor and recycling, the published range of life cycle carbon emissions estimates is reduced by 56% to between 2.9 & 37.3gCO<sub>2</sub>e/kWh. Average values for onshore and offshore wind power are estimated as 16 & 18.2gCO<sub>2</sub>e/kWh respectively after harmonisation and onshore and offshore wind power technologies exhibit similar characteristics in relation to their life cycle carbon emissions. Key differences with previous studies are that this study benefits from inclusion of data from a recently published comprehensive offshore wind farm assessment, and harmonisation is conducted for recycling procedures which results in an increase in the lower band of the range of life cycle carbon emissions estimates.

This chapter sets out to systematically review and harmonise published emission studies of the wind generation industry. This follows on from previous reviews of wind farm LCAs (Lenzen 2002) and particularly that of Dolan & Heath (2012), who use a harmonisation process to characterise and adjust system performance, system boundaries and global warming potentials of the individual GHG species. This chapter will provide further suggestions for best practice in LCAs of wind power with the intention of reducing the large variation present in previously published LCAs (Reap et al. 2008b) in future studies of wind industry activity. The objective is to identify and explain the variability in the results of published LCAs, suggest improvements to the harmonisation process and hence improve the reliability of future LCAs.

The LCA process can produce differences greater than an order of magnitude in estimates of wind farm carbon emissions, and it is clear that the method requires clearer definition for the sake of consistency and credibility of the results. A meta-analysis provides the advantage of being able to combine several studies to address unresolved issues, such as lack of consistency in system boundaries, that result from using the ISO LCA methodology (ISO 14040-44). This has been highlighted in at least one previous study (Reap et al. 2008b) and this chapter adopts a similar approach applied with some variation in to attempt to improve further the reliability of the results.

## **5.1 Method of Review**

### ***5.1.1 Screening of Literature***

A search of the current literature was conducted in order to find published wind LCAs. In line with the approach taken by Dolan and Heath (Dolan & Heath 2012) only papers that were published as scholarly journal articles, trade journal articles, conference proceedings, books or chapters, theses, dissertations, or reports, and were written in English and evaluated electricity as a product were included. In addition to the inclusion criteria outlined above, LCAs published before 2000 were excluded, as were articles that were not free of charge to researchers. This initial search yielded 82 estimates for wind power from 17 references. Following the methodology used elsewhere (Dolan & Heath 2012), the defining characteristics of each study were recorded as were other relevant study specific information. Important system parameters for wind power were also recorded, namely capacity, capacity factor, estimated system lifetime and total lifecycle emissions. This is summarised in Table 5.1.

The scopes of LCAs in the wind industry have differed considerably to date from one study to another. It was suggested as long ago as a decade that uncertainties in lifecycle studies could be reduced by standardising assessment practice (Lenzen 2002). It is particularly difficult to compare lifecycle studies as a result of the different methodologies employed by individual researchers. Therefore, this paper uses the following definitions of the phases of the wind power life cycle:

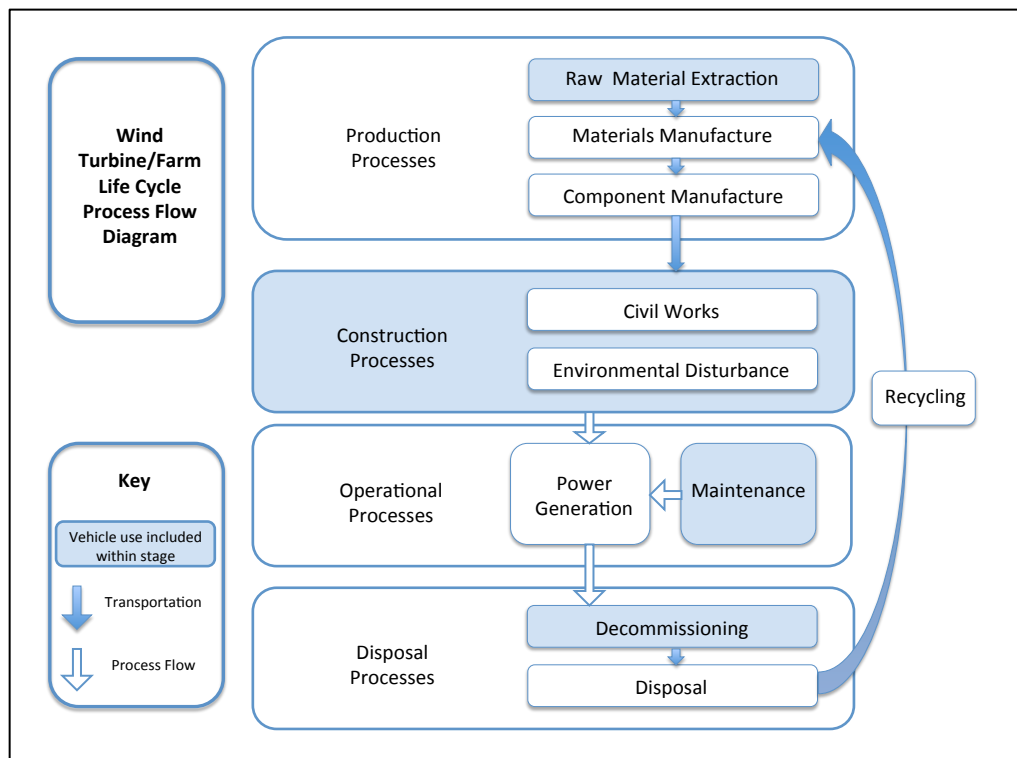
1. **Production:** This includes extraction of raw materials, manufacturing of the foundation, tower, nacelle and blades as well as manufacturing of the transmission grid. Transportation of the raw materials and components to the site is also included.

2. Construction: This includes on-site construction and transport as well as civil works such as access roads and hardstandings. Grid connection should also be included, particularly for offshore installations. Environmental disturbance is also included where appropriate.
3. Operation: This includes all emissions from maintenance such as change of oil, lubrication and transport to and from the turbines. Furthermore, renovation of the turbines is also included.
4. Disposal: This includes dismantling and transport to the final disposal site (recycling, incineration or deposit). At recycling, it is limited to the point where the material is ready for reuse.

A variety of papers have been considered that include both the whole lifecycle of a wind farm project as well as studies that consider only part of the lifecycle such as the turbine manufacture for example. This approach is taken because complete wind farm lifecycle studies are still few and useful information can be taken from studies involving particular lifecycle stages within the whole lifecycle of a project. Figure 5.2 illustrates the process of wind power systems LCAs and can be applied to either wind turbines or whole wind farms. While others (Dolan & Heath 2012) use three main process groups (upstream, ongoing and downstream), this paper splits upstream processes into production and construction and includes the need for transport to be considered where possible, both as its own process and as a unit process within system processes. This is shown in the key in Figure 2. The processes are divided in this way in an attempt to better utilise life cycle GHG assessment as a tool for identifying emissions in individual parts of the system as well as simply providing the life cycle GHG estimate. This is supported for GHG assessment of macro systems (Weidema et al. 2009) and could be developed for micro systems in order to generate improvements and “upgrades” to the system.

The difference between this paper’s process allocation and Dolan and Heath (Dolan & Heath 2012) demonstrates how variability can easily be created when comparing processes that are upstream in nature or even when deciding which individual processes are captured within each system process, for instance by choosing whether or not to include turbine maintenance. This has consistently made it difficult to use GHG estimates to reduce emissions in wind power system since more detail about the processes that are included or excluded is required for each individual estimate.

In order to improve this current situation, this paper moves from the traditional approach to improving estimates through critical surveys, such as that of a review for nuclear power (Sovacool 2008) to utilising a systematic review and meta-analysis such as is employed by Dolan & Heath (2012). The intention is to create more detailed guidance for production of GHG emissions estimates that offer comparability and consistency while also being useful for improvement and upgrading of both the system and the process of estimation.



**Figure 5.1:** Process flow diagram for wind power systems LCAs. Production and Construction processes should be included as a minimum in order to pass the screening process for inclusion. Transport is included both as an individual process, shown by solid arrows and also within specific processes, shown by filled boxes.

Tables 5.1 (onshore) and 5.2 (offshore) detail the studies included within the harmonisation study and their key characteristics.

<i>Study</i>	<i>Wind System</i>	<i>Turbine Capacity (MW)</i>	<i>Capacity Factor</i>	<i>Life-time (Year)</i>	<i>GHG Estimate</i>	<i>Study Type</i>
(Ardente et al. 2008)	onshore	0.66	19%	20	14.8	empirical
(Crawford 2009)	onshore	3	33%	20	32	theoretical
(Crawford 2009)	onshore	0.3	17%	30	35	theoretical
(D'Souza et al. 2011)	onshore	3	43%	20	7	theoretical
(D'Souza et al. 2011)	onshore	3	43%	20	7.4	theoretical
(D'Souza et al. 2011)	onshore	3	35%	20	8.6	theoretical
(D'Souza et al. 2011)	offshore	2.5	40%	20	9	theoretical
(Guezuraga et al. 2012)	onshore	1.8	21%	20	8.8	empirical
(Guezuraga et al. 2012)	onshore	2	34%	20	9.7	empirical
(Guezuraga et al. 2012)	onshore	2	20%	20	16.7	theoretical
(Guezuraga et al. 2012)	onshore	2	34%	20	17.4	theoretical
(Guezuraga et al. 2012)	onshore	2	34%	20	23.3	theoretical
(Guezuraga et al. 2012)	onshore	2	34%	20	38.3	theoretical
(Hondo 2005)	onshore	0.3	20%	50	15	theoretical
(Hondo 2005)	onshore	0.4	25%	30	16	theoretical
(Hondo 2005)	onshore	0.4	23%	30	18	theoretical
(Hondo 2005)	onshore	0.4	20%	30	20.3	theoretical
(Hondo 2005)	onshore	0.4	20%	50	21	theoretical
(Hondo 2005)	onshore	0.4	17%	30	24	theoretical
(Hondo 2005)	onshore	0.3	25%	30	24	theoretical
(Hondo 2005)	onshore	0.3	23%	30	26	theoretical
(Hondo 2005)	onshore	0.3	20%	20	27	theoretical
(Hondo 2005)	onshore	0.4	15%	30	27	theoretical
(Hondo 2005)	onshore	0.3	20%	30	29.5	theoretical
(Hondo 2005)	onshore	0.85	34%	20	35	theoretical
(Hondo 2005)	onshore	0.3	15%	30	39	theoretical
(Hondo 2005)	onshore	0.4	20%	20	40	theoretical
(Hondo 2005)	onshore	0.3	20%	10	49	theoretical
(Hondo 2005)	onshore	0.4	20%	10	72	theoretical
(Jungbluth et al. 2005)	onshore	0.8	20%	20	11	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	55%	20	2	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	68%	20	2	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	71%	20	2	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	42%	20	3	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	46%	20	3	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	55%	20	3	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	68%	20	3	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	71%	20	3	theoretical

**Table 5.1:** Onshore wind farm assessments included within harmonisation study (1)

<i>Study</i>	<i>Wind System</i>	<i>Turbine Capacity (MW)</i>	<i>Capacity Factor</i>	<i>Life-time (Year)</i>	<i>GHG Estimate</i>	<i>Study Type</i>
(Lenzen & Wachsmann 2004)	onshore	0.6	46%	20	4	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	42%	20	4	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	68%	20	8	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	71%	20	8	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	55%	20	10	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	46%	20	12	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	42%	20	13	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	68%	20	15	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	71%	20	16	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	55%	20	20	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	46%	20	26	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	42%	20	27	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	25%	20	45	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	26%	20	48	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	20%	20	61	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	17%	20	77	theoretical
(Lenzen & Wachsmann 2004)	onshore	0.6	15%	20	81	theoretical
(Lewis Wind 2006)	onshore	3.6	35%	20	24.6	empirical
(Martinez et al. 2009)	onshore	2	23%	20	6.2	theoretical
(Martinez et al. 2009)	onshore	2	23%	20	6.6	empirical
(Martinez et al. 2009)	onshore	2	23%	20	9.3	theoretical
(Pehnt 2006)	onshore	3	43%	20	9	theoretical
(Pehnt 2006)	onshore	1.5	30%	20	11	theoretical
(Schleisner 2000)	onshore	0.5	25%	20	9.7	empirical
(Tremeac & Meunier 2009)	onshore	4.5	30%	20	12.1	theoretical
(Tremeac & Meunier 2009)	onshore	4.5	30%	20	15.8	theoretical
(Tremeac & Meunier 2009)	onshore	4.5	30%	20	21.2	theoretical
(Vestas Wind Systems A/S 2006a)	onshore	1.65	41%	20	7.1	theoretical
(Vestas Wind Systems A/S 2006b)	onshore	3	54%	20	4.9	theoretical
(Wang & Sun 2012)	onshore	3	30%	20	6.0	empirical
(Wang & Sun 2012)	onshore	1.65	41%	20	8.2	empirical

**Table 5.2:** Onshore wind farm assessments included within harmonisation study (2)



<i>Study</i>	<i>Wind System</i>	<i>Turbine Capacity (MW)</i>	<i>Capacity Factor</i>	<i>Life-time (Year)</i>	<i>GHG Estimate</i>	<i>Study Type</i>
(Jungbluth et al. 2005)	offshore	2	30%	20	13	theoretical
(Vestas Wind Systems A/S 2006b)	offshore	3	54%	20	5.5	theoretical
(Wagner et al. 2011)	offshore	5	45%	20	24.1	theoretical
(Wagner et al. 2011)	offshore	5	45%	20	28.0	theoretical
(Wagner et al. 2011)	offshore	5	45%	20	29.2	theoretical
(Wagner et al. 2011)	offshore	5	48%	20	29.7	theoretical
(Wagner et al. 2011)	offshore	5	45%	20	32	empirical
(Wagner et al. 2011)	offshore	5	41%	20	34.6	theoretical
(Wang & Sun 2012)	offshore	3	54%	20	5.0	empirical
(Schleisner 2000)	offshore	0.5	29%	20	17	empirical
(Weinzettel et al. 2009)	deep offshore	5	53%	20	11.6	theoretical
(Weinzettel et al. 2009)	deep offshore	5	53%	20	12.2	theoretical
(Weinzettel et al. 2009)	deep offshore	2	30%	20	13.7	theoretical

**Table 5.3:** Offshore wind farm assessments included within harmonisation study

### 5.1.2 Harmonisation Process

The harmonisation process used in this paper is partly derived from Dolan & Heath (2012) and from the LCA Harmonisation Project developed by the National Renewable Energy Laboratory (2012). The less-intensive (or light) method of harmonisation is used herein in order to align with Dolan & Heath (2012) for ease of comparison, however there are some reasoned differences which will be outlined in the following sections. The light harmonisation was used for wind power due to the range of published emissions estimates being up to 10% of the mean value for pulverised coal generation (Whitaker et al. 2012a), illustrating that published variability should be considered significant. This is further outlined by Dolan & Heath (2012) in their supporting information and is considered sufficient here for use in this comparable study. The standard deviation (SD) and interquartile range (IQR) of published estimates of life cycle GHG emissions in gCO<sub>2</sub>e/kWh were both greater than 50% of the mean value of published estimates. As regional grids de-carbonise and renewable power systems increase in capacity, more extensive harmonisation will be desirable in order to improve accuracy and confidence in LCAs.

Published GHG emission estimates were taken as reported in their source publication. Estimates were included only if published in milliperson-equivalents/kWh, or equivalent units, and if the calculation steps were detailed within the published study. Estimates published in the common functional unit found within the literature of grams of carbon dioxide-equivalents per kilowatt-hour (gCO<sub>2</sub>e/kWh) were most applicable to this review. This is generally true for power generation estimates but could be made a standard requirement throughout the power sector for GHG emission estimates. Finally, the GHG emission estimates should be reported numerically in preference to graphically for use and indeed for future standardisation of the GHG emission estimation procedure. These rules were applied by the previous study (Dolan & Heath 2012) and are recommended here as a significant move towards standardisation.

### 5.1.3 Harmonisation Parameters

Following the method in Dolan & Heath (2012), equation 6 was used for calculating life cycle GHG emission estimates for wind power systems:

$$\text{Life Cycle GHG Emissions} = \frac{\text{Lifetime emissions}}{\text{Capacity factor} \times 8760 \text{ hours/year} \times \text{Lifetime} \times \text{Nameplate capacity}} \quad (6)$$

**Where:**

*lifetime emissions (kgCO<sub>2</sub>e), life cycle GHG emissions (kgCO<sub>2</sub>e/kWh), capacity factor (%), lifetime (years), and nameplate capacity (kW)*

Grams of carbon dioxide equivalent include relative global warming potentials of methane (CH<sub>4</sub>) and nitrates (N<sub>2</sub>O). The global warming potential of these gases is not individually assessed in this study since previous results show that this parameter had an insignificant (less than 1%) effect on variability and central tendency after harmonisation (Dolan & Heath 2012).

Equation 6 provides a clear representation of how lifetime and capacity factor affect the life cycle GHG emission estimates by scaling the denominator. Any addition or subtraction resulting from system boundary harmonisation affects the numerator directly. The two sets of parameters, lifetime and capacity factor, and system boundary, will be used for harmonisation in this study. Harmonisation of lifetime and capacity

factor are conducted together since results for these parameters are presented individually by Dolan & Heath (2012) that showed a 2% reduction in the median value of published GHG emission estimates and less than 1% reduction in the total range of estimates for wind power technologies. This study will yield different estimates, resulting from grouping these two parameters into a single combined harmonisation step.

Statistical measures are used to assess the results of harmonisation in order to remain consistent with previous studies. The median value is the key metric for presenting central tendency. The mean is also shown in some results but the median is preferred due to the positive skew of the dataset, as found by Dolan & Heath (2012). The interquartile range (IQR = 75<sup>th</sup> percentile – 25<sup>th</sup> percentile) is also presented in order to show variability but the full range is also presented in the results in order to fully characterise the variability of results. A decrease in these two measures presents effective harmonisation for GHG emission estimates for wind power and so is expected in these results. Standard deviation of estimates is also recorded in both the previous study and this paper for comparison between results and to characterise them more clearly.

It should be noted that the majority of the references used in this study employ process analysis for life cycle GHG emission estimates. This tends to mean that estimates are lower than those of hybrid economic input-output methods due to system boundary truncation (Suh et al. 2006). More specifically in wind power assessment, this can result in underestimation of wind turbine GHG emission estimates of up to 50% (Crawford 2009) and so the upper range of GHG emission estimates is more likely to be representative of the actual life cycle GHG emissions of wind power.

#### **5.1.4 Harmonisation of Operational Life and Capacity Factor**

Life cycle GHG emission estimates were harmonised for the parameters, lifetime of wind power generation and capacity factor of generation. Lifetimes ranged from 10 - 50 years in the literature but 20 years was the most regular lifetime considered and is the recommended design lifetime for wind farms (Hassan 2008; D'Souza et al. 2011) and so should be considered the standard lifetime to be used in GHG emission estimates. This also aligns well with the process of GHG emission estimation resulting from the

life cycles of photovoltaic (PV) systems or battery systems for instance. Certain studies use lifetime as a parameter in their sensitivity analysis (Hondo 2005) but a baseline lifetime of 20 years is recommended for standardisation and is being used by wind industry assessors and companies (Vestas Wind Systems A/S 2006a). GHG emission estimates were harmonised by proportionally scaling the lifetime power output while holding the life cycle emissions estimate constant to maximise synergy with previous studies (Dolan & Heath 2012). Maintenance-related emissions are not considered when the harmonisation process causes changes to the lifetime of the wind power system. Maintenance procedures would undoubtedly change if a wind farm were to remain operational for longer than the design life (20 years) of components, but due to the uncertainty in how these procedures may alter, it is not considered in this study or previous similar studies.

The capacity factor of wind power is the ratio of actual electricity generated to the maximum potential electricity generation (nameplate capacity multiplied by 8760 hours per year). The more operational hours a turbine/farm can generate electricity per year, the higher the capacity factor. In reality, wind farms will have different capacity factors due to local and regional environmental factors (Lenzen & Wachsmann 2004), maintenance variations and possible generation degradation and grid curtailment (Guezuraga et al. 2012). However for the purpose of this study, capacity factors are averaged for onshore and offshore sites in order to assess the impact of assuming capacity factors on the GHG emission estimate if the specific capacity factor for a site is not known. Indeed, since LCA is context-specific, it is not possible to know the exact capacity factor of a wind turbine/farm before obtaining operational information; this could be considered too late for the decision making process. The assumed capacity factors for Dolan & Heath (2012) were 30% for onshore and 40% offshore. This study assumes capacity factors of 35% and 44% for onshore and offshore respectively in order to offer a different dataset of results for this harmonisation step and to better align with average capacity factors seen from the published estimates that are used in this chapter's study (36% for onshore and 44% for offshore). The mean capacity factor for the studies is equally representative of likely capacity factors for onshore and offshore sites, while also still being equally susceptible to the same lack of specific characteristics for individual GHG emission estimations. Dolan & Heath (2012) also suggest figures close to these for "modern turbines deployed in high wind class zones" but other references also suggest some individual capacity factors as high as 71% (Lenzen & Wachsmann

2004). Therefore, those estimations that specified different capacity factors to those outlined for this study were changed through this harmonisation process, along with the lifetime of the system if it was also different to the specified 20 years. This process is less time consuming than that used in previous studies.

#### **5.1.5 Harmonisation of System Boundary**

Life cycle GHG emission estimates were harmonised for the recycling phase of the wind power life cycle. Where individual turbines were analysed (7 references) as opposed to whole wind farms, downstream emissions were accounted for generally as a result of using databases such as Ecoinvent (Ecoinvent 2012) for primary information. Hence it was also difficult to deduce how extensively emissions were covered and it was decided that recycling should only be harmonised where it was missing from both the system processes, and individual unit processes, and was not included within the available data. Some references consider different scenarios that remove end of life credits resulting from recycling. Where this is the case, these estimates have not been harmonised since recycling has been included in an estimate specific to that reference's scenario. When databases are used, it should be explicitly noted whether recycling is included for each substantive material and whether this detail is specific for wind power systems or specific for the material in question since these may be different numbers.

Life cycle emission estimates are not generally displayed in a common format and life cycle processes are often not clearly defined in the published literature. While Dolan and Heath's study (Dolan & Heath 2012) adds to a number of studies for ongoing and downstream processes, it may be too difficult to achieve this given the incomplete nature of many of the current studies. However, there may be a need for some studies to be harmonised for recycling where no recycling has been accounted for in the analysis of life cycle impacts. The mean recycling life cycle emissions is expected to be a negative number as it represents carbon emissions saved by recovering materials to avoid the requirement of new raw materials into the upstream processes of future wind power systems. The results will not use a single figure as an arbitrary add-on (or in this case subtraction) value because the recycling life cycle is proportional to the total material requirements for the wind power system and therefore is proportional to the whole system size and the materials used for individual case studies.

### **5.1.6 Cumulative Harmonisation of all Parameters**

Life cycle GHG emission estimates were harmonised for the recycling phase. The final harmonisation procedure used in this study was to harmonise the lifetime, capacity factor and system boundary parameters consecutively. This was to assess whether some harmonisation procedures counteracted each other in their combined effect.

## **5.2 Results**

### **5.2.1 Summary of Published Literature**

The 82 life cycle GHG emission estimates used in this study are extracted from 17 references and show a median of 15gCO<sub>2</sub>e/kWh, IQR of 19gCO<sub>2</sub>e/kWh, and a range of 79gCO<sub>2</sub>e/kWh. These figures are similar but not equal to those found by previous harmonisation studies (Dolan & Heath 2012). The difference is assumed to be due to the more exclusive selection criteria used to identify the samples included in this study. The range of values, however, remains the same, suggesting that this study included a reasonable number of estimates within the bounds of previous work. This is also characterised by the slightly larger IQR (+7gCO<sub>2</sub>e/kWh). This number represents the middle 50% of the published estimates lying within 19gCO<sub>2</sub>e/kWh of each other. This can be compared to the mean for nuclear power of 66gCO<sub>2</sub>e/kWh (Sovacool 2008) with a range of 286.6gCO<sub>2</sub>e/kWh and other traditional technologies, such as coal-fired power generation in the region of 1000gCO<sub>2</sub>e/kWh (Whitaker et al. 2012b).

Considering onshore and offshore wind power systems independently, it can be seen that while onshore estimates are far more numerous in the literature, both systems exhibit similar statistical characteristics. Of the 68 estimates for onshore systems, the median is 15gCO<sub>2</sub>e/kWh and IQR is 18.7gCO<sub>2</sub>e/kWh. Of the 14 estimates for offshore systems, the median is 15.3gCO<sub>2</sub>e/kWh and the IQR is 19.2gCO<sub>2</sub>e/kWh. This supports the hypothesis that while offshore wind power systems are currently more complex in relation to their upstream engineering, maintenance procedures and decommissioning, the total life cycle GHG emissions are comparable due to the increased power output from offshore sites. This study's IQR and range were both larger than those of Dolan & Heath (2012) which appears to be due to the inclusion in this study of a recent study (Wagner et al. 2011) which estimates life cycle GHG emissions from a real site located off the coast of Germany and has larger estimates than other previous studies.

The range for offshore systems is far smaller than that of onshore systems which could be due to the smaller number of estimates for offshore systems, but may also be due to the improved development of life cycle GHG emission estimation over the more recent period during which offshore wind power systems have also developed.

A number of studies include analyses that could be considered more frequently in life cycle GHG emission estimates. For instance, power generation degradation and grid curtailment (Guezuraga et al. 2012), environmental disturbance upstream (Lewis Wind 2006) and differing downstream scenarios (Lenzen & Wachsman 2004; D'Souza et al. 2011). These will be returned to in the discussion section of this chapter since it is believed that lessons can be taken from these particular studies in relation to any standardisation or guidance for future wind power system life cycle GHG emission estimation.

### **5.2.2 Harmonisation Results**

The harmonisation process was performed in a series of steps. Tables 5.3, 5.4 and 5.5 show the statistical data obtained from the harmonisation process for all estimates, onshore estimates and offshore estimates respectively. The harmonisation steps can be seen in figures 5.2 and 5.3 for onshore and offshore systems respectively. Each step is shown independently and represents the effect that harmonisation category has on the published estimates while the final step is a cumulative harmonisation whereby the steps are conducted consecutively. Changes relate to each step's effect on the estimates from published data. It can be seen that harmonisation for variations in capacity factor and lifetime has the greatest effect on the published data, reducing the range and SD by 57% and 37% respectively for all estimates.

<i>Statistical Measure</i> (gCO <sub>2</sub> e/kWh)	<i>As Published</i> <i>life cycle</i> <i>GHG</i>	<i>Harmonised by</i> <i>capacity factor</i> <i>and lifetime</i>	<i>Harmonised by</i> <i>system boundary</i>	<i>Harmonised</i> <i>by all</i>
Mean	19.8	17.1	18.7	16.4
SD	16.7	10.6	15.6	10.1
Minimum	2.0	3.1	1.8	2.9
25th percentile	8.0	7.6	7.4	7.6
Median	15.0	15.4	13.9	14.3
75th Percentile	27.0	25.5	25.0	23.4
Maximum	81.0	37.4	74.9	37.3
IQR	19.0	17.9	17.6	15.8
Range	79.0	34.3	73.0	34.5
Change in mean	n/a	-14%	-6%	-17%
Change in SD	n/a	-37%	-7%	-40%
Change in Median	n/a	3%	-8%	-5%
Change in IQR	n/a	-6%	-8%	-17%
Change in range	n/a	-57%	-8%	-56%
Count of estimates	82	81	43	82
Count in references	17	15	3	17

**Table 5.4:** Summary statistics for each harmonisation step for all wind farm estimates

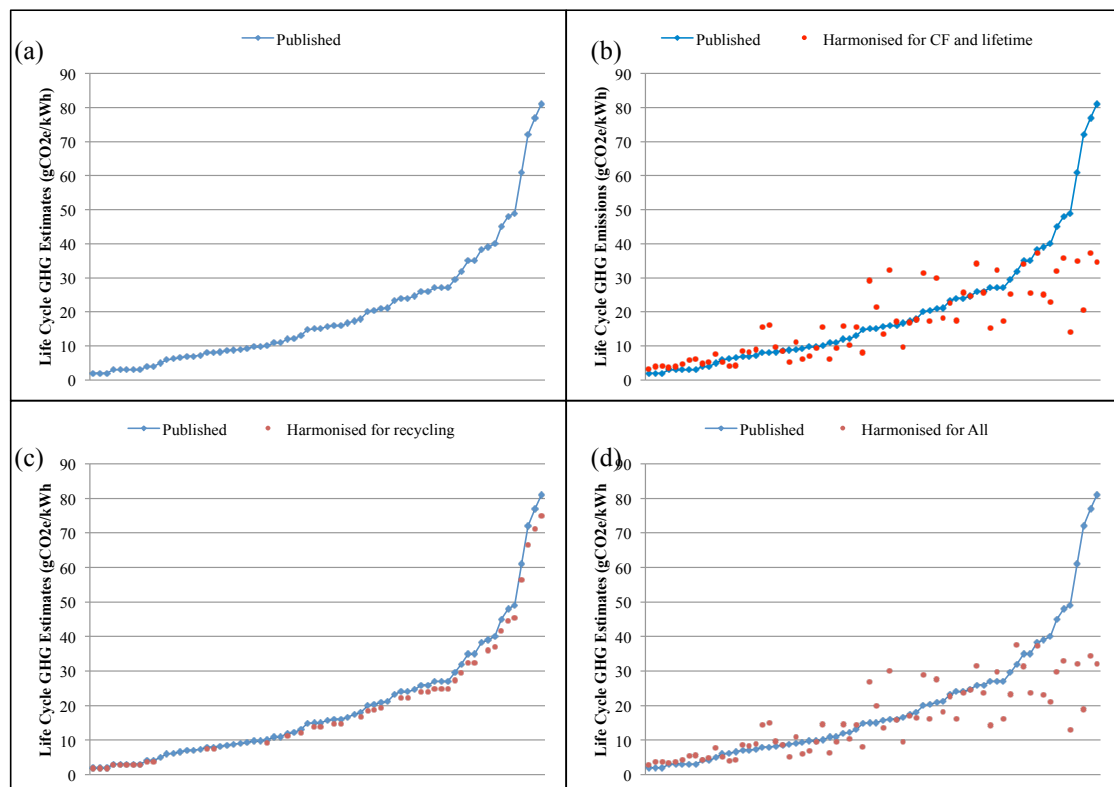
<i>Statistical Measure</i> (gCO <sub>2</sub> e/kWh)	<i>As Published</i> <i>life cycle</i> <i>GHG</i>	<i>Harmonised by</i> <i>capacity factor</i> <i>and lifetime</i>	<i>Harmonised by</i> <i>system boundary</i>	<i>Harmonised</i> <i>by all</i>
Mean	20.0	19.6	22.5	16.0
SD	18.0	10.7	19.1	10.1
Minimum	2.0	3.1	1.8	2.9
25th percentile	7.4	6.9	7.4	6.9
Median	15.0	15.7	19.1	14.4
75th Percentile	26.0	25.3	29.6	23.5
Maximum	81.0	37.4	74.9	37.6
IQR	18.7	18.4	22.2	16.6
Range	79.0	34.3	73.0	34.7
Change in mean	n/a	-2%	12%	-20%
Change in SD	n/a	-41%	7%	-44%
Change in Median	n/a	4%	27%	-4%
Change in IQR	n/a	-2%	19%	-11%
Change in range	n/a	-57%	-8%	-56%
Count of estimates	68	67	43	68
Count in references	15	14	3	15

**Table 5.5:** Summary statistics for each harmonisation step for onshore wind farm estimates

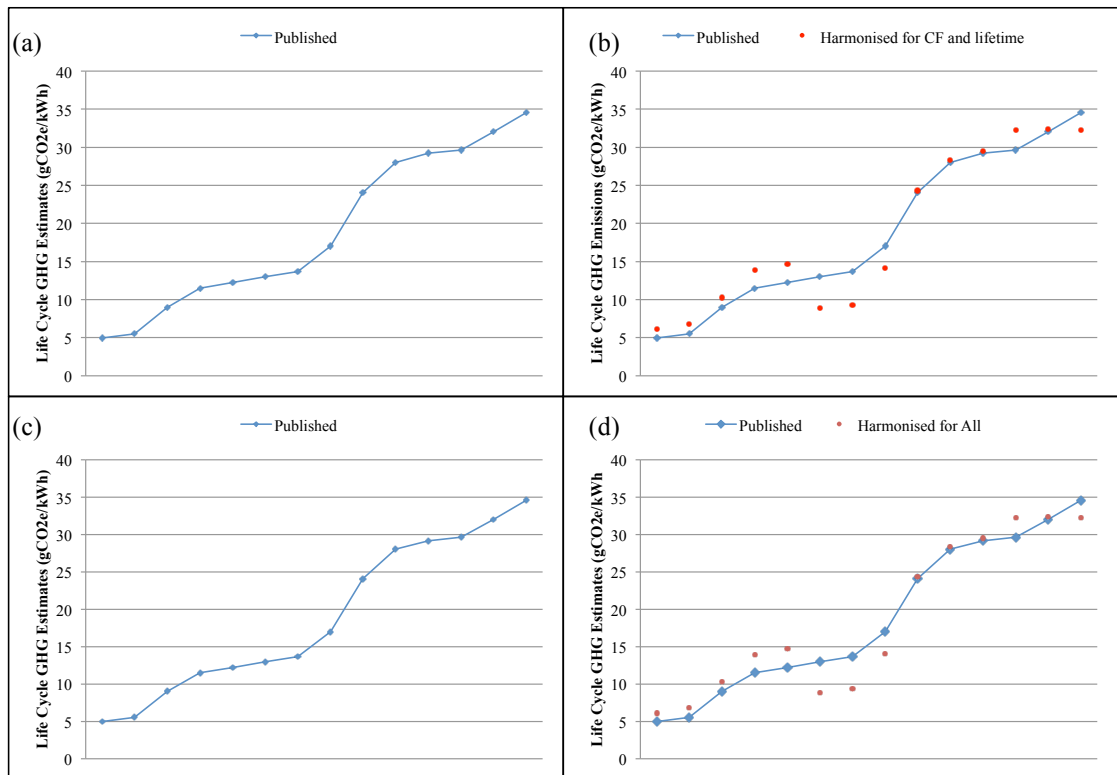


<i>Statistical Measure</i> (gCO <sub>2</sub> e/kWh)	<i>As Published</i> <i>life cycle</i> <i>GHG</i>	<i>Harmonised by</i> <i>capacity factor</i> <i>and lifetime</i>	<i>Harmonised by</i> <i>system boundary</i>	<i>Harmonised</i> <i>by all</i>
Mean	18.9	18.8	18.9	18.2
SD	10.3	10.4	10.3	9.8
Minimum	5.0	6.1	5.0	6.1
25th percentile	10.3	9.1	10.3	9.1
Median	15.3	14.4	15.3	14.4
75th Percentile	29.4	28.9	29.4	26.3
Maximum	34.6	32.4	34.6	32.3
IQR	19.2	19.8	19.2	17.2
Range	29.6	26.3	29.6	26.2
Change in mean	n/a	0%	0%	-4%
Change in SD	n/a	1%	0%	-5%
Change in Median	n/a	-6%	0%	-6%
Change in IQR	n/a	3%	0%	-10%
Change in range	n/a	-11%	0%	-11%
Count of estimates	14	14	0	14
Count in references	7	7	0	7

**Table 5.6:** Summary statistics for each harmonisation step for offshore wind farm estimates



**Figure 5.2:** Life cycle GHG emission estimates for onshore wind farms. (a) all published estimates, (b) harmonised for capacity factor and lifetime, (c) harmonised for missing system boundary to include recycling and (d) cumulative harmonisation of all previous parameters.



**Figure 5.3:** Life cycle GHG emission estimates for offshore wind farms. (a) all published estimates, (b) harmonised for capacity factor and lifetime, (c) harmonised for missing system boundary to include recycling (not required here) and (d) cumulative harmonisation of all previous parameters.

### 5.2.3 Harmonisation of Operating Life and Capacity Factor

Of the 82 estimates considered in this study, all but one were harmonised for both onshore and offshore mean capacity factors. For the lifetime of the wind power system, 14 estimates were corrected to the proposed 20 years. Both corrections were made in a single combined step. These harmonisation categories had the tendency to reduce the range of estimates significantly, in agreement with previous studies. Figures 5.2 & 5.3 above show this reduction for onshore and offshore systems respectively. The range reduced by 57% for all estimates while the IQR reduced by 5.8% to 17.9gCO<sub>2e</sub>/kWh. Hence, the capacity factor and lifetime chosen by the assessor has a significant impact on total life cycle GHG emission estimates. It can also be deduced by separating the effect of harmonising capacity factor from harmonising lifetime that the capacity factor choice has a larger effect on life cycle emissions estimation.

*“The wind conditions are the single most important parameter for the environmental performance of a wind turbine” (Vattenfall 2010).*

#### 5.2.4 Harmonisation of System Boundary

Of the 82 estimates considered in this study, 43 were corrected for recycling processes in the life cycle. This is related to 3 references (Crawford 2009; Hondo 2005; Lenzen & Wachsman 2004) and resulted in a decrease in the range and IQR of estimates by 8% and reduction in the mean of 6%. Only onshore systems were corrected since this study found that all offshore studies contained allowances for the recycling processes. Onshore estimates showed an increase in IQR of 19% but showed the same decrease in range of 8%. The mean recycling life cycle emissions was -1.47gCO<sub>2</sub>e/kWh. Table 5.4 summarises the reductions (%) for harmonisation for all estimates, for onshore and offshore systems.

	All Estimates	Onshore	Offshore
<b>Harmonisation for system boundary</b>	-7.45%	-7.55%	-7.14%
<b>Harmonisation for all</b>	-8.60%	-7.70%	-7.18%

**Table 5.7:** Reductions in percentages of total estimates for harmonisation of system boundary (recycling) and for final harmonisation step, cumulative harmonisation

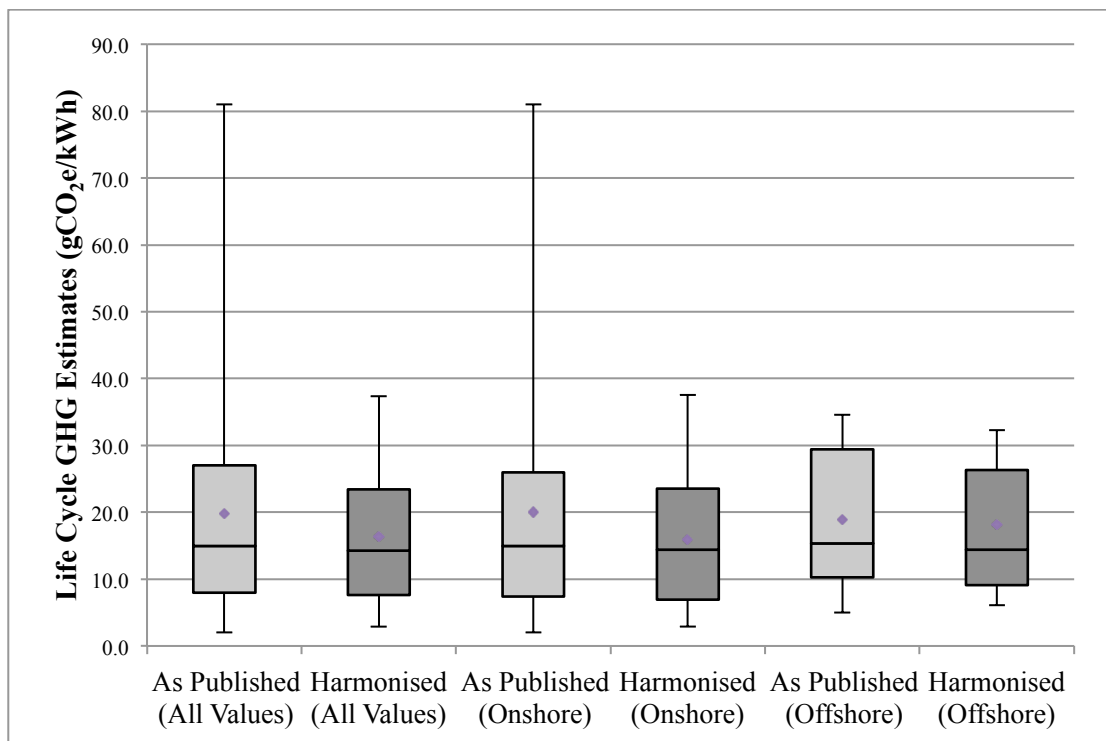
Estimates were harmonised where recycling was not considered. This resulted in the reductions by the percentages given in Table 5.4 of the total published estimates. These figures represent the average saving of carbon emissions by recycling materials at the end of the life cycle of wind power systems. The cumulative harmonisation factors shown were also used in the final step, as outlined below.

#### 5.2.5 Cumulative Harmonisation of All Parameters

The final combined harmonisation procedure for capacity factor, lifetime and recycling processes reduced the distribution of all estimates considerably. The range of estimates has reduced by 56% to 34.5gCO<sub>2</sub>e/kWh. This is still approximately double the mean of the data (16.2gCO<sub>2</sub>e/kWh) but is considerably less than before harmonisation. The IQR reduced by 17% to 15.8gCO<sub>2</sub>e/kWh. The median value reduced only slightly from 15 to 14.3gCO<sub>2</sub>e/kWh, supporting Dolan & Heath's (2012) results that the central tendency of estimates stayed reasonably constant. It can be seen from the individual harmonisation steps that capacity factor and lifetime were the main contributors to these changes and capacity factor appears to be the most influential when considering Dolan & Heath's

(2012) results for their individual steps alongside these results. While this study uses a similar approach to previous studies (Dolan & Heath 2012), it does have some differences in approach. However the results of both studies support each other's methodology and provide further evidence that harmonisation increases the accuracy of life cycle GHG emission estimates without dramatically changing the central tendency of results. Figures 5.2 and 5.3 illustrate the reduction in the range of estimates for each step and clearly demonstrate the individual effects of the chosen parameters.

A key difference in these results to Dolan & Heath (2012) is seen in the narrowing of the total range which can be seen in Figure 5.5 due to an increase in the minimum values after harmonisation for both onshore and offshore systems. This is unlike the previous study that shows an increase in range at the system boundary harmonisation level. This is shown in numerical form in the summary statistics in Table 5.3 (p127) and can be compared with (Dolan & Heath's 2012) results. A further difference is due to this papers attempt at harmonisation of system boundaries and including recycling as a proportion of the total life cycle emissions estimate.



**Figure 5.4:** Comparison of central tendency and spread of published life cycle GHG emission estimates and final harmonised estimates. The lower line represents the minimum, the lowest edge of the box is the 25<sup>th</sup> quartile, the middle line of the box is the median, the top edge of the box is the 75<sup>th</sup> quartile and the top line is the maximum. The diamond represents the mean value.

## **5.3 Discussion**

### **5.3.1 Comparison of Onshore and Offshore**

The results of the harmonisation suggest a close relationship between onshore and offshore systems with regard to a number of statistical indicators. While onshore systems have a larger range, due in part to the age of the technology, wind site variability, system design and also perhaps due to some studies reporting relatively large numbers of estimates (Lenzen & Wachsmann 2004; Hondo 2005) both technology types exhibit similar IQRs both before and after harmonisation. These are 16.6gCO<sub>2</sub>e/kWh and 17.2gCO<sub>2</sub>e/kWh for onshore and offshore types respectively, representing a change of -11% and -10% IQR respectively. The median for both types is 14.4gCO<sub>2</sub>e/kWh after harmonisation. This agrees with Dolan & Heath's (2012) suggestion that the two system types are not dramatically different in relation to their life cycle GHG emissions. This study contains data for offshore systems (Wagner et al. 2011) that is not available to the previous harmonisation study (Dolan & Heath 2012) and provides larger than average estimates for offshore wind systems.

While offshore systems are behind in their development, relative to onshore systems, they are able to deliver greater capacity factors meaning that life cycle GHG characteristics are comparable. This suggests that one standard life cycle GHG emission estimation tool could be developed for both technologies. While this study can only speak for the references included within it, there appears from this harmonisation that there is closer agreement within the literature, as well as literature reviews, as to the life cycle GHG emission range of wind power systems, allowing for more confidence in the reliability of advice to informed decision making. However the range of values for emissions remains high relative to the median values and means.

### **5.3.2 Limitations**

A study of this nature inevitably restricts its scope to avoid overly complex results. Accordingly, in this study, life cycle GHG emissions are the only environmental effect considered for wind systems. However, since ISO LCA considers other impact categories, future studies should be developed in order to evaluate other environmental effects of wind farms.

A meta-analysis uses specific information from available studies in order to identify common trends. While this harmonisation process offers a tighter range of estimates, it does not necessarily offer insight into common trends or aid in the development of a standard framework for conducting life cycle GHG emission estimates. This study suggests a framework based on its results and lessons gained from reviewing individual estimates at the end of this section. This will improve future estimations as well as future harmonisation studies.

Dolan & Heath (2012) provide a number of insights into the potential issues surrounding the harmonisation process used such as clustering bias from large numbers of estimates coming from single references, or sample size limitations, especially with respect to offshore systems due to the relatively recent nature of the technology. If the two references that provide the most estimates are removed (Lenzen & Wachsman 2004; Hondo 2005) the mean for all harmonised estimates reduces to 15.28gCO<sub>2</sub>e/kWh, a drop of 6.5%. While this is significant it is small in comparison to the range of emissions estimates. These issues will not be further covered in this study. The harmonisation process does not check for accuracy within each individual estimate. As a result of such a harmonisation process, an evaluation tool for new estimates should be developed in order to more rapidly assess their reliability.

### **5.3.3 Pooling Theoretical and Empirical Estimates**

Due to the nature of life cycle assessment, it is not always clear in the literature whether a study should be considered empirical or theoretical. It may be more accurate to see the majority of studies as part theoretical, part empirical. This is especially true with the technologies and materials specified within studies since specific data is not always available for either unit processes of the life cycle or system processes. While this, and the previous harmonisation attempts, list studies as one or the other it may not be entirely valid for all parts of the life cycle assessment.

It may be better to review future wind system studies at other scales such as on an individual turbine or wind farm basis. 43 estimates in this study are from turbine studies, while the remaining 39 are farms. Farms have mean life cycle GHG emissions of 17.7gCO<sub>2</sub>e/kWh while turbines have mean emissions of 15gCO<sub>2</sub>e/kWh. This is not considerably different but does show that wind farms have higher life cycle emissions

per kWh as would be expected. As harmonisation develops, it may be more suitable to harmonise for onshore and offshore farms separately to individual turbines. However for the time being it remains prudent to group onshore and offshore farms and turbine studies together and will remain so until more results are available.

#### **5.3.4 Accuracy of the Central Tendency of Literature Estimates to True Life Cycle GHG Emissions**

Assessing wind power with regards to its life cycle GHG emissions presents the technology as very favourable compared to more traditional technologies, especially fossil fuel generation (World Energy Council 2004). However, this does not consider the consequences of adding intermittent power generation to a power network in sufficient depth. More analysis should be undertaken in order to assess how wind power systems affect the other technologies currently installed in supply networks. In particular thermal plants produce less gCO<sub>2</sub>e/kWh at higher operating loads (Spath & Mann 2000) so that reducing their operational load in response to wind generation surges should be accounted for in a comprehensive study of wind power emissions. Increasing wind power capacity in a supply network will reduce the operational hours or operating loads of thermal plants in the medium term while also fluctuating their efficiencies in the short term as they respond to intermittency. This could be seen as a reduction in the emissions saving affect from electricity with wind power in the system. This can be seen in a study that suggests that offshore wind in Germany could result in up to 70gCO<sub>2</sub>/kWh ((Pehnt et al. 2008); Figure 6) due to operating the supply network with offshore wind being integrated at a low carbon dioxide price scenario in a carbon trading market. At a high scenario, this would be reduced to 18gCO<sub>2</sub>/kWh. These figures are important in comparing with total life cycle GHG emissions for wind power systems prior to integration. More research is needed in this area if the global impact on the overall electricity supply network CO<sub>2</sub>e emissions of increased wind generation deployment is to be fully understood.

#### **5.3.5 Developing a Standard Assessment Framework**

This chapter calls for standardisation in order to facilitate improvements to the technologies and processes under consideration as well as to ensure consistency and a reduction in variability of life cycle estimates of a given technology. The harmonisation process described in this paper illustrates that a number of important parameters have a

large influence on total life cycle GHG emission estimates. In particular, capacity factor choice is highly influential. However, little work has been done to propose a framework that supports continued improvement of the estimation process. It is suggested that all life cycle GHG emission estimates should include the life cycle phases present in Figure 5.1. This will allow for more accurate harmonisation of system boundaries in future studies and also provide more useful data for technological improvements through GHG assessment of individual life cycle phases. Also noted from the literature are important areas that require estimation in the life cycle GHG estimation process. These are:

- Clarity in published estimates. This refers to all areas of estimation. Data origins should be clearly shown, as well as all assumptions made throughout the assessment. Results should be given in gCO<sub>2</sub>e/kWh for all wind power generation technologies as standard over the lifetime of 20 years or in an alternative standard unit.
- Environmental disturbance. While this may not be relevant for all wind power systems, it should be addressed in order to ensure completeness. For instance, peat disturbance (Lewis Wind 2006) may be present, resulting in higher life cycle GHG associated emissions.
- Degradation of power generation and grid curtailment may present a 2% annual degradation of power generation from wind power systems as well as 30% reduction due to grid curtailment (Guezuraga et al. 2012). These effects may increase life cycle GHG emissions by up to 43% and should be considered in all future estimates, using region-specific information where possible.

#### **5.4 Conclusions**

Life cycle GHG emissions of wind power systems assessed in this study range from 2 to 81gCO<sub>2</sub>e/kWh. While this could be considered a small absolute range for a power generation technology, it represents a difference of almost two orders of magnitude from the smallest to the largest value. It is made much smaller through applying the harmonisation process for capacity factor and lifetime, and recycling processes (2.9 to 37.3gCO<sub>2</sub>e/kWh). The IQR for estimates reduced by 17% following harmonisation that is much lower than the decrease in range, suggesting that average estimates in the IQR were relatively reliable. This is an important result for decision-making. Capacity factor and lifetime are seen to cause the largest effect on total life cycle GHG emission estimates, with capacity factor choice being particular influential.



Harmonisation of life cycle GHG emission estimates is shown to decrease the variability of estimates. However, accuracy of estimates is not assessed and there are other factors that should be considered when reviewing their reliability.

There was relatively close agreement between onshore and offshore wind power systems in relation to their life cycle GHG emissions. This suggests that emissions from onshore and offshore installations are not substantially different. However, with offshore installations currently being the fastest area of development in wind power, particularly in Northern Europe, more studies will be required to further support or refute this claim. In particular, the additional life cycle stages involved with offshore installations such as the civil works required for grid connection and power transmission via direct current, if further than 50km from shore, should be focussed on to align GHG estimation with development in the wind industry.

There are too great a number of process-based LCAs in relation to wind power systems which are in conflict with LCA practitioners' suggestions (Crawford 2009) and could result in large truncation errors. Further studies should be conducted by hybrid economic LCA as well as consequential LCAs in order to better understand the interaction of wind power with the rest of the power supply technologies currently available on electricity supply networks. In particular the effects of intermittency on thermal generation plants should be studied further.

## **Chapter 6 – Case Study of Ormonde Offshore Wind Farm**

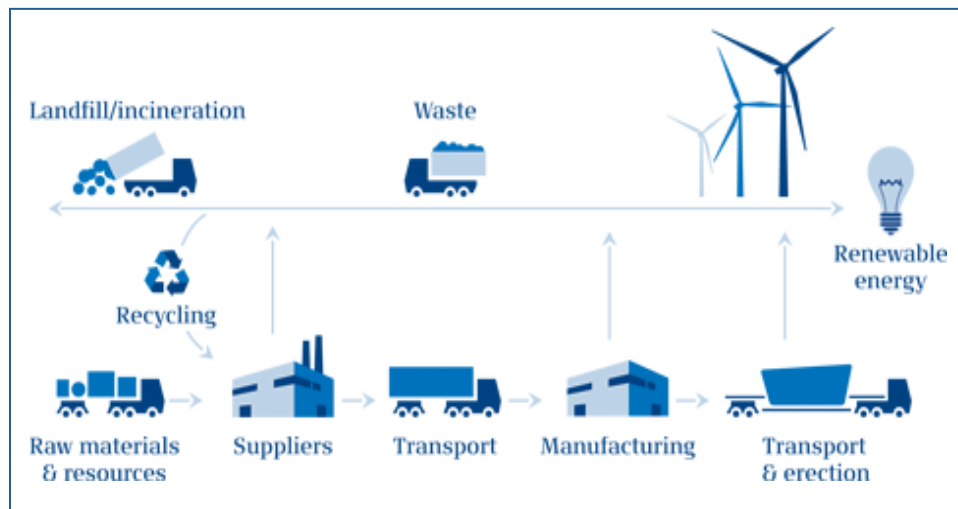
This chapter takes the lessons learned from reviewing life cycle assessment methodology in Chapter 4 and the statistical analysis of historic life cycle GHG estimates of wind power in Chapter 5 to conduct a full life cycle study of Ormonde Offshore Wind Farm in the Irish Sea. Three methodologies are considered as well as sensitivity analysis of those variables that were highlighted in Chapter 5 in order to effectively estimate a likely range of life cycle GHG emissions that can be attributed to this wind farm and provide another estimate of life cycle emissions for offshore wind power, of which there are many fewer examples, as seen in the previous chapter.

### **6.1 Introduction**

The ability of wind power to generate electricity while reducing greenhouse gas (GHG) emissions may be of vital importance for economies over the coming decades. As discussed in Chapter 5, large variability in estimates of GHG emissions still exists in published wind power life cycle studies (Dolan & Heath 2012) while the number of offshore wind life cycle studies is relatively few, mainly due to the younger age of the technology.

One of the largest offshore installations to date, Ormonde Offshore Wind farm has a total installed capacity of 150MW and began generating power to the UK grid in August 2011. The installation was conducted in one phase, with offshore construction beginning in May 2010. Ormonde consists of 30 5MW REPower turbines that have 126m diameter blades. Annual power generation is expected to be 508GWh. This equates to a capacity factor for the farm of 38.7% (Vattenfall 2010). This is below the average offshore wind farm capacity factor of 44%, which taken from a study of wind farm studies in the Chapter 5. This case study represents one of the largest wind installations to date to have a life cycle estimation conducted.

Life cycle studies estimate the potential environmental impacts throughout a project's life cycle from raw material acquisition through production, use, end-of-life treatment recycling and final disposal, as shown in Figure 6.1.



**Figure 6.1:** Life Cycle of a wind turbine (D'Souza et al. 2011)

While life cycle studies are valuable for the understanding of a project, they cannot be the only assessment of different power generation technologies. Issues such as noise pollution or impacts on wildlife need to be considered through mechanisms such as environmental impact assessments. Social and economic factors are also not covered within a life cycle study of this nature; therefore other assessments should be used to accompany it.

Using the International Organisation for Standardisation (ISO) 14040/44 standards, LCA consists of four phases (ISO 2006a; ISO 2006b):

1. Goal and scope (framework and objective of the study)
2. Life cycle inventory (analysis of mass and energy flows from operations along the product's value chain)
3. Life cycle impact assessment (evaluation of the environmental relevance, e.g. Global Warming Potential (GWP))
4. Interpretation (e.g. optimisation potential).

The goal and scope stage outlines the reasoning for the study, the uses of the study's results, the boundary conditions, the data requirements and the assumptions made to analyse the product system under consideration, in this case the Ormonde Offshore Wind Farm. The goal of the study is to answer the specific questions that have been raised by the target audience and the stakeholders involved, while considering potential uses of the study's results. The scope of the study defines the system's boundary in terms of technological, geographical, and temporal coverage of the study, attributes of

the product system, and the level of detail and the complexity addressed by the study. Unresolved issues are still present in this phase of LCA, such as allocation of impacts to processes when using either a consequential or attributional LCA methodology (Finnveden et al. 2009). This study uses an attributional LCA approach since the product system is a specific wind farm and so this reduces the uncertainties inherent in consequential LCA and will be more suitable for creating a standard framework due to consequential LCA being context-specific.

The life cycle inventory (LCI) stage quantitatively and qualitatively analyses the materials and energy used (inputs) as well as the products and by-products generated and the environmental releases and the wastes to be treated (outputs) for the system being studied. The LCI data can be used on its own to: understand total emissions, wastes and resource use associated with the material or the product being studied; improve production or product performance; or be further analysed and interpreted to provide insights into the potential environmental impacts from the system (life cycle impact assessment and interpretation, LCIA) (D'Souza et al. 2011).

It is intended that this study will act as a baseline for LCA studies in the UK for wind power for assessing wind farm performance in relation to life cycle aspects and to enable and help integrate the environmental dimension in product design, target setting and decision making.

## **6.2 Goal of Study**

The goal of this study is to estimate the GHG emissions associated with the production of electricity from the 150MW Ormonde Offshore Wind Farm in Cumbria. An additional goal of this study is to assess the effect of different methodological approaches to the same assessment. This will be conducted using three different methodologies in order to highlight areas where LCAs are time and resource-intensive. Firstly, a process-based analysis is conducted. Secondly, a novel cost-based analysis is conducted using aggregated data for offshore wind power. Finally, a novel hybrid analysis is conducted by using information from the cost-based analysis to fill known data gaps in the process-based analysis.

The installation consists of thirty 5MW REPower turbines and lies between 9.5 and 14km from shore. The GHG emissions will be determined in a life cycle perspective, including production of components from raw materials to factory, erection and installation of the wind turbines and site infrastructure (for example, power cabling and substations), operational and maintenance procedures, transport relating to the farm, losses during transmission and end of life treatment.

A further goal of this study is to develop a framework for future life cycle GHG estimation studies of offshore wind power for the UK, improving on past LCA review studies and in particular utilising the harmonisation approach originally developed by NREL and previous reviews of LCA methodology as discussed in the previous chapter.

The results from Chapter 5 help inform this life cycle study and help to develop a life cycle GHG emission estimation tool for UK wind installations. Results from this life cycle study will:

- Further improve life cycle estimation of wind power and develop a life cycle framework for UK wind power
- Identify possible optimisation and improvement areas of technology and infrastructure
- Identify areas of wind power with the highest associated CO<sub>2</sub>e emissions

### **6.3 LCA Methodologies**

The following three methodologies will be used on the same scope of the system (outlined in Section 6.4) in order to assess the effect of methodological approach.

#### **6.3.1 *Process-Based Analysis***

The traditional and most commonly used life cycle assessment approach used for wind power has been process-based analysis (Dolan & Heath 2012). This approach is concerned with the physical units (e.g. kg of CO<sub>2</sub> per kg of material) that input to and output from the system under consideration. It has generally been considered more accurate and relevant to the system being analysed (Crawford 2009). This method is considered a bottom-up approach and is data and time-intensive as a result. By requiring more relevant data to the system, the result has difficulty in acquiring all the necessary data for all life cycle phases. As well as this, the methodology also creates a number of truncation errors at lower order production steps of the life cycle (Wiedmann 2009) and

it is also suggested that such errors can account for up to 87% incompleteness (Crawford 2009). It will be shown in Section 6.16 that while providing more relevant data for this study in general, its approach has resulted in data gaps and under-estimation by an unknown amount.

Physical units for the materials used in the various elements of the wind farm are taken from information provided by the operator of the wind farm, Vattenfall, or calculated from design information as described in Section 6.6. This information is then used in conjunction with system processes information for the production of these materials from Ecoinvent v2.0 that cover EU processes. As a comparison of datasets, Bath University's ICE Database v2.0 is also used in order to assess the difference between EU specific data from the Ecoinvent v2.0 dataset and UK specific data from this dataset. This will assess the effect of choice of dataset on life cycle associated emissions estimation.

### **6.3.2 Cost-Based Analysis**

An approach to life cycle assessment is cost-based analysis. This traditionally utilises monetary units (e.g. kg of CO<sub>2</sub> released in the production of one unit worth of value – Euros in this instance). This approach requires averaged data for the activities and products in the sector of the economy concerned in the study or a breakdown of average costs for the project concerned - in this case offshore wind farm. This can be collated in Input-Output tables that capture economic information on supply, use, activities and products for a given region. This is averaged for whole economies and is considered a top-down approach to life cycle assessment. While potentially reducing data gaps that are seen in process-based analysis, it offers greater data uncertainty due to aggregation across sectors. In order to tackle this, a novel cost-based analysis technique is suggested here, using information on the cost breakdown of a typical UK offshore wind farm project.

Firstly, the total cost of Ormonde Wind Farm is divided across defined categories of the wind farm using a breakdown of costs of offshore wind power in the UK (RAB 2010). These categories are: development and consent; turbine excluding tower; balance of plant; installation and commissioning; and operation and maintenance. The costs also include services (e.g. vessels, cranes), insurance and other overheads, which may be

otherwise missed by a process-based analysis. End of life phases are difficult to assess due to a lack of data on the costs of decommissioning and recycling a wind farm at present. Decommissioning costs of the whole farm are assumed to be equal to those of installation and commissioning. An assumption is made for recycling net benefits (sale of scrap metals and components) based on Hughes, (2012a; p16) who suggests that the residual value of a wind turbine may be around 10% of its initial value. In this case, this equals €18.2m net benefit to the project at the end of its life. There are also up to two sub-categories below each of these and splits of labour, materials and other costs are given or derived in the RAB (2010) report. Since the financial cost in Euros of the various elements of an offshore wind farm can be derived from the breakdown of costs, these can be used to create an emissions/Euro rate. This is done in three instances in order to test the range of likely rates that can be derived. The following steps were taken to create these emissions rates:

1. Total costs for the wind farm in question, or element of wind farm, are derived from the cost breakdown
2. Total life cycle GHG emissions for a wind farm, or element of wind farm, are estimated using process-based analysis (using Section 6.3.1)
3. Division of total emissions by total costs for a wind farm, or element, is conducted

Tables 6.1 and 6.2 provide cost breakdown information for capital and operational expenditure for a typical UK offshore wind farm (RAB 2010).

<i>Category</i>	<i>Category Component</i>				
	<i>Category Percentage of Cost</i>	<i>Labour</i>	<i>Material</i>	<i>Other</i>	<i>Cost (Euros)</i>
<b>Operation</b>	<b>15%</b>	<b>10.00%</b>	<b>3.80%</b>	<b>0.80%</b>	<b>30,480,000</b>
Remote	8%	5.00%	1.90%	0.40%	16,256,000
Local	8%	5.00%	1.90%	0.40%	16,256,000
<b>Maintenance</b>	<b>38%</b>	<b>11.00%</b>	<b>3.90%</b>	<b>22.90%</b>	<b>77,216,000</b>
Remote	12%	3.00%	1.20%	6.90%	24,384,000
Local	27%	8.00%	2.70%	16.00%	54,864,000
<b>Port Activities</b>	<b>31%</b>	<b>10.70%</b>	<b>4.70%</b>	<b>15.80%</b>	<b>62,992,000</b>
Remote	8%	2.70%	1.20%	3.80%	16,256,000
Local	23%	8.00%	3.50%	12.00%	46,736,000
<b>License Fees</b>	<b>3.80%</b>	<b>0.40%</b>	<b>0.40%</b>	<b>3.10%</b>	<b>7,721,600</b>
<b>Other Costs</b>	<b>12%</b>	<b>1.20%</b>	<b>1.20%</b>	<b>9.00%</b>	<b>24,384,000</b>
				<b>Total</b>	<b>202.8m Euros</b>

**Table 6.1:** Breakdown of operational costs (OPEX) for a typical UK offshore wind farm (RAB 2010). Greyed sections represent data that is not accounted for during process-based analysis

<i>Category</i>	<i>Category Percentage of Cost</i>	<i>Category Component</i>			<i>Cost</i>
		<i>Labour</i>	<i>Material</i>	<i>Other</i>	
<b>Development and Consent</b>	<b>4%</b>	<b>2.40%</b>	<b>0.90%</b>	<b>0.80%</b>	<b>22,080,000</b>
Environmental Survey	0.30%	0.09%	0.03%	0.20%	1,656,000
Sea Bed Survey	0.60%	0.11%	0.13%	0.40%	3,312,000
<i>Geophysical</i>	0.10%	0.01%	0.08%	0.00%	552,000
<i>Geotechnical</i>	0.50%	0.10%	0.05%	0.40%	2,760,000
Met Mast	0.30%	0.08%	0.10%	0.06%	1,656,000
Development Services	2.80%	2.10%	0.60%	0.17%	15,456,000
<i>Engineering</i>	0.90%	0.70%	0.20%	0.07%	4,968,000
<i>Other Services</i>	1.90%	1.40%	0.40%	0.10%	10,488,000
<b>Turbine</b>	<b>33%</b>	<b>17.00%</b>	<b>10.00%</b>	<b>6.00%</b>	<b>182,160,000</b>
Rotor	11%	5.40%	3.10%	2.40%	60,720,000
Blades	7%	4.00%	1.60%	1.70%	38,640,000
Hub Assembly	4%	1.40%	1.50%	0.70%	19,872,000
Nacelle	22%	11.40%	7.40%	3.30%	121,440,000
Gearbox	9%	4.70%	3.30%	1.40%	49,680,000
Electrical System	8%	4.10%	2.70%	1.20%	44,160,000
Other	5%	2.60%	1.40%	0.70%	25,392,000
<b>Rest of Plant</b>	<b>37%</b>	<b>9.00%</b>	<b>21.00%</b>	<b>6.00%</b>	<b>204,240,000</b>
Tower	6%	1.20%	3.70%	1.20%	33,120,000
Foundations	16%	3.90%	9.30%	2.30%	88,320,000
Cables	5%	0.50%	3.20%	1.60%	27,600,000
Inter Array	1%	0.10%	0.80%	0.40%	7,728,000
Export	4%	0.40%	2.40%	1.20%	22,632,000
Offshore Substations	7%	2.60%	3.50%	0.60%	38,640,000
Electrical System	5%	2.20%	2.70%	0.50%	27,600,000
Other	1%	0.40%	0.80%	0.10%	7,728,000
Onshore Electrical	2.70%	1.10%	1.30%	0.27%	14,904,000
Electrical System	2.00%	0.80%	1.00%	0.20%	11,040,000
Other	0.70%	0.30%	0.30%	0.07%	3,864,000
<b>Installation/Commissioning</b>	<b>26%</b>	<b>6.00%</b>	<b>2.00%</b>	<b>18.0%</b>	<b>143,520,000</b>
Foundations	7%	1.40%	0.30%	5.00%	38,640,000
Cables	9%	2.10%	0.80%	7.00%	49,680,000
Turbines	9%	2.80%	0.50%	6.00%	49,680,000
Offshore Substations	0.70%	0.20%	0.03%	0.50%	3,864,000
				<b>Total</b>	<b>552m Euros</b>

**Table 6.2:** Cost breakdown of capital expenditure (CAPEX) for a typical UK offshore wind farm (RAB 2010). Greyed sections represent data that is not accounted for during process-based analysis

Since previous wind farm LCAs are generally split into four main categories (production, construction, operations and maintenance, and decommissioning), these life cycle stages will be used in this instance. The relative costs for each of these will be taken from the information provided in tables 6.1 and 6.2 and life cycle GHG estimates from the process-based analysis conducted in this chapter will be assigned to each of these life cycle phases. Since costs for the wind farm elements are split into capital expenditure (CAPEX) and operations and maintenance (OPEX), the embodied GHG



emissions from the process-based analysis for ‘*production*’ and ‘*construction*’ will be used together to calculate the GHG intensity for this phase of the life cycle while ‘*operations and maintenance*’ and ‘*decommissioning*’ from the process-based analysis will be kept separate and used to find their own GHG intensities for these phases of the life cycle of the offshore wind farm. Table 6.3 shows an example of how this will be calculated.

<i>Life Cycle Phase</i>	<i>Embodied GHG Emissions (kgCO<sub>2</sub>e)</i> <i>A</i>	<i>Cost (Euros - €)</i> <i>B</i>	<i>Phase GHG Intensity (kgCO<sub>2</sub>e/€)</i> <i>C</i>
Production	139,150,000	408m	<b>0.255</b>

**Table 6.3:** Example of determining GHG Intensity for a novel cost-based analysis

Embodied GHG emissions (A) will be calculated using a traditional process-based life cycle analysis as outlined in Section 6.3.1 and will provide specific primary information on total associated GHG emissions for each phase of the life cycle of the offshore wind farm. This figure will be divided by the total cost for that phase (B), found by multiplying cost breakdown information in tables 6.1 and 6.2. The GHG intensity per Euro spent (C) will be calculated from total embodied GHG emissions and cost for each life cycle phase. The GHG intensity per Euro spent (C) will be multiplied by the cost breakdown for Ormonde Offshore wind farm specifically in order to find total emissions for each category (and sub-category) of the wind farm. These values are then divided by total estimated power generation of Ormonde offshore wind farm to give life cycle greenhouse gas emissions estimates for the farm in terms of kgCO<sub>2</sub>/kWh. This is the functional unit of this study and can be compared both to other forms of generation and indeed other estimates of wind power from either other sites as well as from estimates derived from other methodologies in this instance.

A number of phases of the life cycle that are included in the cost breakdown for an offshore wind farm have not been included in the process-based analysis due to a lack of data. It is these missing life cycle categories that will then be included in the novel hybrid analysis using the methodology outlined in Section 6.3.3.

### **6.3.3 Novel Hybrid Analysis**

A hybrid analysis is an approach to life cycle GHG assessment utilising both monetary and physical units in order to account for carbon associated emissions throughout the life cycle of a system. As already mentioned in Chapter 4, Section 4.6.2, hybrid analysis adds value to LCAs of systems and impacts are better assessed through use of both economic and ecological data (Suh 2004). Two other studies also agree with the above point and suggest that for a relatively small increase in complexity for the study, considerable advantages are achieved. These include a better understanding of the system being assessed (Jiusto 2006) and overcoming the issue of data gaps in process-based LCA, while avoiding such disadvantages of product-based LCA as using aggregated data (Rowley et al. 2009). A number of issues in using hybrid approaches are covered in Section 4.6.2, relating to knowledge of integrating two distinct approaches.

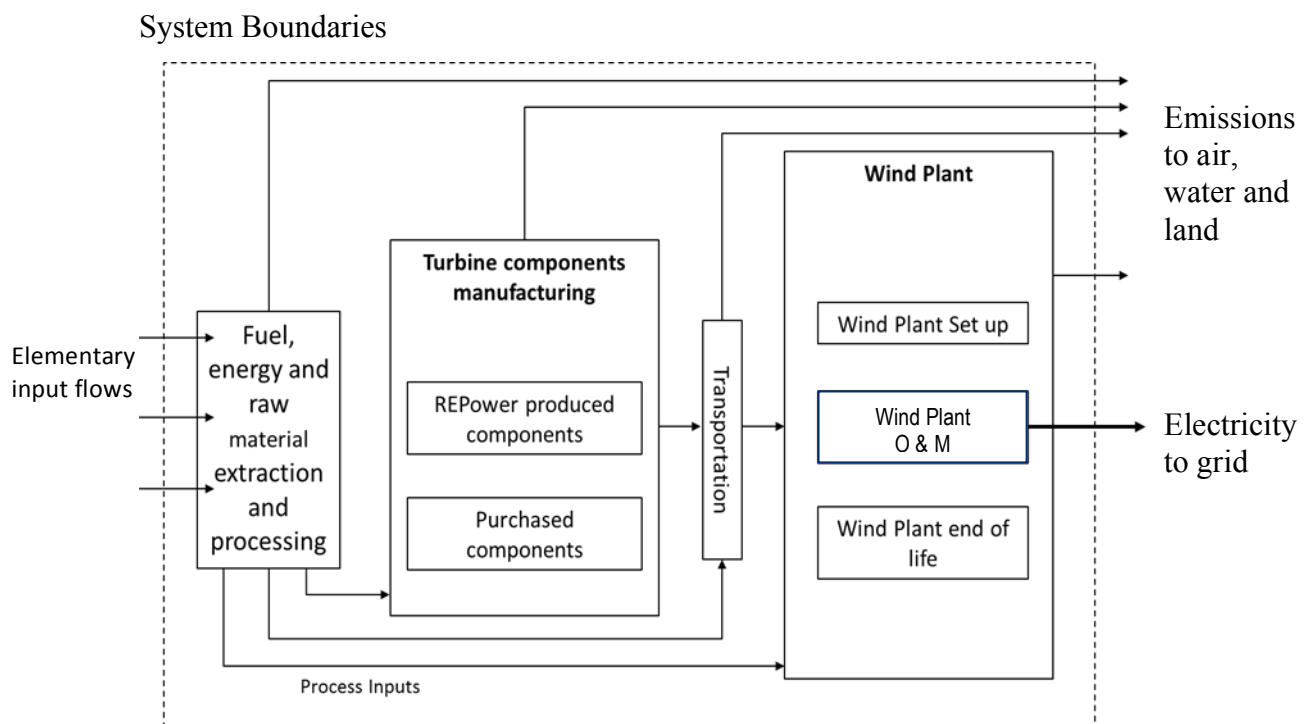
In this study, a novel hybrid analysis is developed using the following approach. The process-based analysis is taken as already outlined in Section 6.3.1. By being open about the data gaps from this approach, it can be seen that a number of areas are not covered in the LCA either through lack of data or by the methodology not relating to specific activities, such as the labour requirements of construction or the planning procedures that are highlighted in the cost breakdown information in tables 6.1 and 6.2 (RAB 2010) and presented in this study using greyed squares within the tables 6.1 and 6.2. This allows for a more complete LCA to be conducted as well as greater certainty for users of the study due to a greater level of completeness. Based on Section 4.6.2 in Chapter 4, particular advantages achieved from using hybrid approaches include a better understanding of the system being assessed and overcoming the issue of data gaps in material-based (process-based) LCAs, while avoiding such disadvantages of cost-based (product-based) LCAs as using aggregated data. In this case for instance, no information is available for support structures such as the port office in terms of materials used in construction but financial costs are known, as well as costs associated with the workforce. This information can be included in a hybrid assessment and offers greater coverage of the life cycle phases of Ormonde Offshore Wind Farm.

Using the cost-based analysis in conjunction with process-based data helps to reduce likely truncation errors from using only physical units, similar to those errors discussed in the literature (Crawford 2009).

#### 6.4 Scope of Study

This study is a cradle-to-grave study based on three methodologies as outlined in Section 6.3, estimating the life cycle GHG emissions associated with generating power from the 150MW Ormonde Offshore Wind Farm consisting of thirty 5MW wind turbines over its full project lifetime. The scope of the study is presented in Figure 6.2.

This will include where possible the extraction of raw materials, manufacturing processes of all components, production of the assembled turbines, associated logistics, use until dismantling and disposal of the turbines and infrastructure. Production and maintenance of the adjoining infrastructure and capital goods such as site offices and installation vessels have been excluded from this study in the process-based analysis but some consideration of them can be made in the cost-based analysis and subsequently, the novel hybrid analysis. A provision can be made in a sensitivity analysis of a process-based analysis for this, albeit with greater uncertainty. Estimation of total life cycle impacts relating to this from other methodologies can be made from historical studies such as those reviewed in Chapter 5. Use of process-based analysis in this way results in an exclusion of areas of a project such as adjoining infrastructure based on ISO methodology.



**Figure 6.2:** Scope of Ormonde Wind Farm LCA. Please note O & M refers to Operations and Maintenance. (Adapted from D'Souza et al. (2011))

The following processes have been considered in this study:

- Production of the parts of the wind turbine and associated infrastructure. Most of the information on parts and components (materials, weights, manufacturing operations, end of life practices) was provided by the operator of the farm, Vattenfall and obtained from design information and supplier data. Where information is lacking, average compositions have been assumed or available publically from literature.
- Manufacturing processes through use of emissions databases, Ecoinvent v. 2.0 and Bath University's ICE database, v. 2.0 as well as specific information regarding their location.
- Transportation of turbine components to wind plant site
- Site servicing and operations (including transport)
- Replacement parts during maintenance and operation
- Use phase power production from Vattenfall estimations based on their 98% availability targets.
- End of life treatment of turbines

## **6.5 Functional Unit**

In order to compare life cycle environmental impacts and in particular, GHG emissions associated with electricity production from different plants, it is important to define a functional unit. With wind power, it has also been suggested that specifying wind conditions is also important (D'Souza et al. 2011) in order to make an accurate comparison.

The REPower turbines operate in medium to high wind conditions (IEC I and II) at the site that has a 10 year global average wind speed of 9.78 m/s for hub height of 100m (4cOffshore 2014) therefore results from this study should be seen in the context of high wind conditions. Other wind conditions are considered in the sensitivity analysis through use of differing capacity factors. While the specific wind speeds have not been used to calculate the corresponding capacity factor of Ormonde farm in this instance, the provided estimated annual power generation of 508GWh/year equates to a capacity factor of 38.66%, equivalent to a farm in an average wind speed of 9.3 m/s, corresponding to medium to high wind conditions (D'Souza et al. 2011) and so also offering a conservative figure for the capacity factor.

To enable comparisons to other technologies on a consistent basis, the functional unit for this study is defined as:

*1 kWh of electricity delivered to the grid by the wind power installation, Ormonde Offshore Wind farm.*

## **6.6 System Description**

The boundaries of the wind farm are taken to be the point at which the electrical power is delivered to the existing onshore network, at the Heysham Power Station substation at Heysham, UK in this case. All cabling up to, but not including the existing substation, is included since it was installed within the wind farm project.

## **6.7 Life Cycle Stages**

The life cycle of the wind farm is split into four life cycle stages. Chapter 5, Figure 5.1 shows the stages that are used in this study for all methodologies. As seen in Chapter 5, in order to effectively analyse wind farms, it is important to retain this life cycle division throughout the assessment process. This allows for individual analysis of the different life cycle stages and will improve both the technology progression and indeed life cycle GHG assessment application. An overview of the assessment approach of each life cycle stage is given in Section 6.4 and below.

1. Production: This includes extraction of raw materials, manufacturing of the foundation, tower, nacelle and blades as well as manufacturing of the transmission grid. Transportation of the raw materials and components to the site should also be included.
2. Construction: This includes on-site construction and transport as well as civil works such as access roads and hardstandings. Grid connection should also be included, particularly for offshore installations. Environmental disturbance is also included where appropriate.
3. Operation: This should include all emissions from maintenance such as change of oil, lubrication and transport to and from the turbines. Furthermore, renovation of the turbines should be included.

4. Disposal: This includes dismantling and transport to the final disposal site (recycling, incineration or deposit). At recycling, it is limited to the point where the material is ready for reuse.

### **6.7.1 Production**

This phase of the life cycle considers the production of raw materials and consequently, the manufacturing and assembly of components of wind farm components, such as the foundations, towers, nacelles, blades, cabling and substations. While some studies may call this phase other names, such as manufacturing (D'Souza et al. 2011), this study chooses to classify this phase as production in order to ensure that raw material phases are considered prior to the manufacturing of components. As shown in Figure 5.1 there is also transport involved in this phase of the life cycle but it is important to ensure this only includes transport to and from manufacturing sites and of raw materials. In LCA methodology, this phase can be seen as cradle to gate, referring to the phase of raw material extraction to components being ready to travel to site for installation. Certain studies (D'Souza et al. 2011) do not include transport of raw materials to specific production sites due to their scope not including this phase of the life cycle or looking at a typical wind farm development rather than a specific site such as this study. This is particularly important in order to further inform decisions on locations of future manufacturing sites for the turbines themselves due to the high associated GHG emissions impacts during the manufacturing phase. This should be considered in order to ensure that areas of the life cycle are not missed. Transport of raw materials to production sites may be included when using emissions factors from datasets, such as Ecoinvent that often includes such areas in its system processes for given materials. For example, Ecoinvent includes the whole manufacturing process to produce cement mortar (raw material provision, raw material mixing, packing, and storage), transports to plant, and infrastructure for cement mortar produced at a plant in the EU. This is important to know in order to avoid truncation errors as previously discussed in Chapter 4, Section 4.6.3 and also to avoid double counting as mentioned in 4.6.2.

### **6.7.2 Construction**

This phase of the life cycle includes all component transport to site. This is similar to the allocation applied by some industry LCAs currently (D'Souza et al. 2011) but also by academic papers (Lenzen 2002) who, albeit considering it a small contribution to the total life cycle associated GHG emissions even for large distances, expect it to be

considered. Offshore wind farm sites may change this conception due to differing transport use. Construction of any provision infrastructure such as roads, bridges, turning and working areas are also accounted for in this phase. Again, this is industry practice in the Vestas study already mentioned to a point but is also recommended here in order to account for a potential area of high environmental impact. The Vestas study also ignores processes associated with laying foundations, erecting turbines, laying internal cables, installing/erecting substations and connecting to the existing grid. It has been suggested that 32.5% of total manufacturing associated emissions can be assigned to building works in some instances (Ardente et al. 2008). Important to mention also is the currently lacking assessment of seabed disturbances for offshore installations.

### **6.7.3 *Operations and Maintenance***

This phase concerns all general running of the wind farm as it generates electric power. This includes all emissions from maintenance such as change of oil, lubrication and transport to and from the turbines. Furthermore, renovation of the turbines is also included.

### **6.7.4 *End of Life***

The wind farm is dismantled at the end of its life and remediated to the agreed state as specified in the planning permission. This includes dismantling and transport to the final disposal site (recycling, incineration or deposit). At recycling, it is limited to the point where the material is ready for reuse.

## **6.8 Technology Coverage**

This study conducts a life cycle study of the REPower 5M turbine with 126m rotor diameter, transportation of components to the offshore site, erection of the wind turbines and installation, site operations and maintenance as well as dismantling and scrapping of the wind plant components at the end of the wind farm's life.

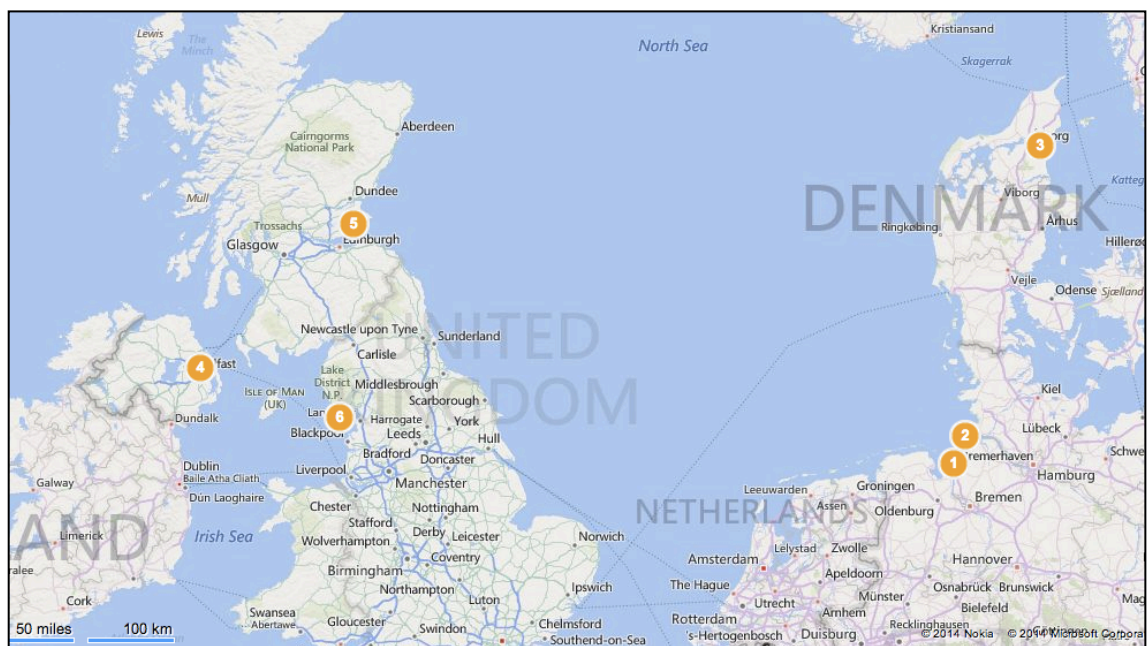
## **6.9 Temporal Coverage**

This study is conducted for the year 2012 when Ormonde Offshore Wind Farm began generating electrical power to the UK grid. From this date, the Wind Farm will be generating low-carbon electrical power and so comparisons with grid electricity should be made from this year. While components and manufacturing took place before this year, it is chosen as a representative year. The latest Ecoinvent dataset available is used which was compiled in May 2010 which fits to the manufacturing and production

timeframe for the Wind Farm since installation of foundations began in early May 2010 and erection of turbines in early 2011.

## 6.10 Geographical Coverage

The study covers production and manufacturing locations in Germany and Denmark. See Figure 6.4 in conjunction with the following European locations. The Nacelles are manufactured in Bremerhaven, Germany (1) while the towers in Cuxhaven, Germany (2). The blades are manufactured in Aalborg, Denmark (3). These elements were transported by vessel for partial assembly and storage at Harland and Wolff, Belfast (4). The foundations were transported from their manufacturing location at Methil, Scotland (5). Finally, the substation was built in Barrow-in-Furness, England (6). All elements were moved from their storage or manufacturing facility to the East Irish Sea site by vessel.



**Figure 6.3:** Map of Geographical locations of manufacture and operations for Ormonde. Bremerhaven, Germany (1). Cuxhaven, Germany (2). Aalborg, Denmark (3). Belfast, NI (4). Methil, Scotland, UK (5). Location of Ormonde Offshore Wind Farm (6).

## 6.11 Data Collection / Completeness

Data have been collected from the operator, Vattenfall and from their main suppliers where possible, in particular REPower for turbine information. This was provided in the form of a previous journal paper (Wagner et al. 2011) and personal correspondence with the authors but primary data was not made available. Information for the cabling and



substation has been collected from Visser and Smit Marine, the installers of the inter-array cabling. These data have been found through discussions and co-operation with relevant personnel at Vattenfall's local site office in Barrow-in-Furness, via technical drawings and from supplier declarations in the form of documents online or publically available. Instances where specific information has been used in this study are:

1. Materials composition of wind farm components (except the turbines themselves)
2. Materials composition of larger purchased components of the wind farm
3. Utilities and materials consumption for wind farm site preparation, operation and maintenance
4. Transport distances from manufacturers to site
5. Fuel use during construction and operational phase supplied by Vattenfall's site office in Barrow-in-Furness.
6. End of life procedures from the Environmental Impact Assessment and Planning Documents.

Where primary data have not been readily available from Vattenfall or their suppliers, secondary data have been used in order to avoid data gaps. Secondary data have also been used via the Ecoinvent dataset for processes that are upstream in the supply chain and for raw material extraction phases. Instances where such data have been used are:

1. Production Data for the Wind Farm
2. Power Grid mix information
3. Production of raw materials
4. 5M turbine carbon associated impacts
5. Manufacturing processes for smaller standard purchased items
6. End of life processes

## **6.12 Cut-off Criteria**

The following cut-off criteria are used in this study to ensure all relevant environmental impacts are represented. These are derived from ISO 14044 Clause 4.2.3.3.3 and represent industry practice in life cycle assessment since it is used by D'Souza et al. (2011) in their LCA of a Vestas wind plant. They define the percentage as 1%, as outlined below. This could be considered as standard for wind farm LCAs since it is being conducted in practice already.

- **Mass** – if a flow is less than 1% of the cumulative mass of all the inputs and outputs (depending on the type of flow) of the LCI model, it may be excluded, provided its environmental relevance is not a concern.
- **Energy** – if a flow is less than 1% of the cumulative energy of all the inputs and outputs (depending on the type of flow) of the LCI model, it may be excluded, provided its environmental relevance is not a concern.
- **Environmental relevance** – if a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it will be included. All material flows which leave the system (emissions) and whose environmental impact is higher than 1% of the whole impact of an impact category that has been considered in the assessment, shall be included.
- The **sum** of the neglected material flows shall not exceed 5% of total mass, energy or environmental relevance.

In actuality, it can be assumed that 100% of the total mass of materials in the REPower 5M 5.0 MW turbine has been accounted for due to the authors' direct communications with REPower during their study (Wagner et al. 2011) and their acquisition of design documents for the turbine. Had this not been the case, results would have been scaled up to 100% of the full mass of the turbine (i.e. the percentage of components not accounted for are assumed to have the average composition of the rest of the turbine). This should be stated in LCA assumptions if it were to be the case in an LCA.

## **6.13 Assumptions**

It should be noted that the following assumptions apply to the main scenario for each methodology. Scenario and sensitivity analyses are outlined in the following Section 6.14.

### ***6.13.1 Lifetime of Wind Farm***

The standard lifetime of the wind farm is assumed to be 20 years. This is in agreement with the planning applications for the wind farm and the assumed design life for the various components of the wind farm, except for some replacement parts such as gearboxes where required during the operational phase. It is also the most common standard lifetime used in historic LCAs of wind farms, as presented in Chapter 5.

### 6.13.2 *Materials Input*

In the course of this study, it has been not been possible to obtain reliable information regarding the degree of recycled content of materials used in the product system for production of components. It is assumed that all materials are made from virgin material. This is a very conservative assumption since a substantial proportion of metal components will actually be derived from secondary sources (D'Souza et al. 2011). During the end-of-life phase of the life cycle, three methods for accounting for recycling of metals are used. These refer to the Inventory of Carbon and Energy (ICE) Version 2.0. Annex B: Methodologies for Recycling. This is particularly true for steel that has a recycled content of 30% in the UK on average and 40% in the EU on average.

### 6.13.3 *End of Life Treatment*

End of Life treatment of the turbine is judged from a variety of sources. It is assumed that the whole turbine is removed from the substructure at the end of life and recovered to onshore facilities. It is unclear what the end of life treatment is for this particular turbine (the REPower 5M turbine) but it is assumed that the turbine is not recycled homogeneously, as others have assumed in their LCAs of wind turbines (D'Souza et al. 2011). Indeed, this industry study of the Vestas V112 3.0MW turbine provides a number of assumptions for recycling. These are used in this study since they have been taken from "expert judgement" and "data from previous studies" conducted by Vestas (D'Souza et al. 2011). As mentioned in D'Souza et al. (2011) study, these figures are supported by the metal industry and the closed-loop approach is preferred to the recycled-content approach.

<i>Material</i>	<i>Treatment</i>
Aluminium	90% recycled + 10% landfilled
Copper	90% recycled + 10% landfilled
Steel	90% recycled + 10% landfilled
Polymers	50% incinerated + 50% landfilled
Lubricants	100% incinerated
Other waste (including concrete)	100% landfilled

**Table 6.4:** Recycling assumptions for materials in wind turbines

As with D'Souza et al. (2011), any metal components that are predominantly mono-material such as tower sections and gears, are assumed to be 98% recycled. This is because the metal will not be 100% recycled due to realistic recycling procedures (Graedel et al. 2011) and also that it has been used in the reference study of the Vestas

turbine. Internal cables from the turbines themselves are 95% recycled but not cables in the seabed as suggested by Vattenfall and their Environmental Impact Assessment (EIA) which states that subsurface cabling will be left in situ at the end of life (Eclipse Energy 2005).

Substructures will be cut above the seabed and removed, as per the EIA for Ormonde Offshore Wind Farm (Eclipse Energy 2005). This is in line with standard practice in the oil and gas sector and is assumed to be the approach adopted by the offshore wind industry.

In order to account for recycling, the ICE database’s recycling methodology (Hammond & Jones 2008) is used and all three approaches adopted in order to assess the different potential results. These results can be seen in Figure 6.5. It should be noted that different methodological choices here directly influence the GHG intensity factor used in the assessment. The default *recycled content* method is used in all baseline assessments in this chapter since this is recommended by Hammond & Jones (2008). This approach creates a GHG intensity factor of 0.71 kgCO<sub>2</sub>e/kg for the recycling of the steel in the farm. For the Ecoinvent results for end of life impacts, the GHG intensity factor of 0.814 kgCO<sub>2</sub>e/kg is used to assess the recycling of all steel in the wind farm not already included in the turbine recycling. This represents steel recycling: scrap iron produced, 10% landfilled, 55% avoided pig iron in a UK context and is less conservative than the ICE database’s calculation for steel in that it provides less of a net benefit when assessing the overall benefits of recycling in relation to the total estimated GHG life cycle emissions of Ormonde wind farm.

<i>Material</i>	<i>Recycled Content Approach</i>	<i>Substitution Method</i>	<i>50:50 Method</i>
	(kgCO <sub>2</sub> e/kg)	(kgCO <sub>2</sub> e/kg)	(kgCO <sub>2</sub> e/kg)
<b>Steel</b>			
General	1.46	0.76	1.11
Coil (sheet) galvanised	1.54	0.78	1.16
Pipe	1.45	0.74	1.10
Steel in Farm	0.71	0.93	0.82

**Table 6.5:** Recycling approaches from ICE Database (Hammond & Jones 2008; Annex B) and calculated GHG intensity factors for recycling steel.

Table 6.6 shows the recyclability of recyclability of the major assemblies of a Vestas V112 wind turbine (D’Souza et al. 2011) and will be used to assume recyclability of REPower 5M turbine in this instance.

<i>Major Assemblies</i>	<i>% of wind turbine by total mass</i>	<i>Total mass of material (kg)</i>
Turbine	100%	594,500
Nacelle (% of wind turbine by weight)	32%	190,240
% recyclability of Nacelle:	87%	
Gearbox (% of Nacelle)	44%	83,706
<b>Steel and iron</b>	<b>99%</b>	<b>82,869</b>
<b>Non-ferrous metals</b>	<b>&lt;1%</b>	
Polymers	<1%	
Electronics	<1%	
Other materials	1%	
Transformer (% of Nacelle)	8%	15,219
<b>Steel and iron</b>	<b>82%</b>	<b>12,480</b>
<b>Non-ferrous metals</b>	<b>10%</b>	<b>1,522</b>
Polymers	8%	
Other materials	<1%	
Generator (% of Nacelle)	7%	13,317
<b>Steel and iron</b>	<b>85%</b>	<b>11,319</b>
<b>Non-ferrous metals</b>	<b>9%</b>	<b>1,199</b>
Polymers	<1%	
Electronics	3%	
Other materials	3%	
Remainder (% of Nacelle)	41%	77,998
<b>Steel and iron</b>	<b>80%</b>	<b>62,399</b>
<b>Non-ferrous metals</b>	<b>10%</b>	<b>7,800</b>
Polymers	1%	
Electronics	3%	
Other materials	6%	
Recyclability: metals >90%		
Rotor (% of wind turbine by weight)	20%	118,900
% recyclability of Rotor	38%	
Blades (% of rotor)	11%	13,079
Polymers and Lacquers	40%	
Ceramic / glass	52%	
Other Materials	8%	
Hub (% of rotor)	9%	10,701
<b>Steel and iron</b>	<b>95%</b>	<b>10,166</b>
<b>Non-ferrous metals</b>	<b>&lt;1%</b>	
Polymers	2%	
Other materials	3%	
Recyclability: metals >90%		
Tower (% of wind turbine by weight)	46%	273,470
% recyclability of Tower	97%	
<b>Steel and iron</b>	<b>99%</b>	<b>270,735</b>
<b>Non-ferrous metals</b>	<b>&lt;1%</b>	
Other materials	<1%	
Recyclability: metals >90%		
% recyclability of Remainder	2%	11,890
	47%	
<b>Steel and iron</b>	<b>28%</b>	<b>3,329</b>
<b>Non-ferrous metals</b>	<b>23%</b>	<b>2,735</b>

**Table 6.6:** Recyclability of the Major Assemblies of wind turbine (D'Souza et al. 2011)

#### **6.13.4 Sulphur hexafluoride**

The production of sulphur hexafluoride gas has not been accounted for in LCAs generally but might be considered in a worst case scenario since the gas would be released to the atmosphere in the event of a blow-out in rare circumstances (D'Souza et al. 2011).

#### **6.13.5 Onboard turbine cabling**

It has not been possible during this study to obtain specific accurate data regarding the onboard cabling in the 5M turbines concerned although it is included in the turbine data as a whole. Subsequently, data regarding the inter-array cabling will be used as a proxy for the onboard wiring, as has been previously done in the Vestas study (D'Souza et al. 2011). This can be seen as conservative since the onboard cabling is considered not to be as complex as the inter-array or export cables for which primary information is used.

#### **6.13.6 Foundations**

Primary information for the materials used for the substructure has been available to this study and therefore no assumptions are required. However, for the end-of-life treatment, it is assumed that the substructure will be cut above the seabed at the base of the jacket leg and removed. This will result in the piles and cement grouting being left in the seabed so it is assumed that no end-of-life treatment is possible for these components of the substructure.

#### **6.13.7 Electrical / Electronic components in turbine**

As with the onboard cabling within the 5M turbines, it has not been possible to obtain primary data for the electrical components within the turbine relating to specific material use. It has been assumed that electronics for control units from Ecoinvent is appropriate to use as a proxy, similarly to the Vestas study's approach. It is felt that this is conservative due to inclusion of housings and printed wiring boards within the system process for the dataset.

#### **6.13.8 Rare Earth Elements**

The following information comes from a recent study by Zero Waste Scotland (2014) into the use of Rare-Earth Elements in wind turbine devices. Rare-Earth elements

(REEs) such as Neodymium are used in certain wind power devices, namely Siemens and Vestas devices and should be included in an accurate carbon and energy assessment. Neodymium and Dysprosium used in the permanent magnets are both REEs and are costly to mine, process and purchase but are essential in some of the direct drive technologies now being employed and have increased efficiency through their high magnetic properties. 95% of REEs currently come from China, who is also considering export quotas on these metals due to continued increases in demand. Housed within the nacelle of the wind turbine, these REEs can contribute up to 200 kilo per nacelle for larger devices and may have a significant market value at end of life. In the case of the 5M REPower turbine, these are not present and therefore are not included in this study.

#### ***6.13.9 Transport***

As shown in Figure 5.1, transport occurs in a number of life cycle phases. These are the extraction of raw materials, the manufacturing and delivery of components to site, the construction phase, the operational phase and the decommissioning phase.

Transport involved in the extraction of raw materials is not explicitly included in this study from primary information due to lack of available data for specific materials going to the manufacturing facilities in Northern Europe. However the Ecoinvent database, used for system processes for individual materials, accounts for some transport in these phases. While not specific to this wind farm, a data gap is not presented through assuming that this data is sufficient, being that it applies to the EU and considers some transport.

This study benefits from having primary data for the fuel use of transport vessels, construction vessels and maintenance vessels from the Barrow Port and Vattenfall's site office. This is valuable information for this study since it shows exact fuel use for specific vessels. Specific distances and fuel use are included in this life cycle study and are presented in Section 6.15.

It has been assumed that decommissioning transport is equal to construction transport through discussions with the site manager at the Barrow Port and since primary

information will not be available for this part of the life cycle until the wind farm has been decommissioned.

#### ***6.13.10 Inventory Analysis***

This LCA follows an attributional approach. All relevant inputs and outputs from the component processes are accounted for using either primary or secondary data if required. The Software, Simapro is commonly used for life cycle assessment and Ecoinvent, the European database commonly used by practitioners for environmental life cycle studies. Verification of Ecoinvent has also been attempted through using a UK database for materials, the ICE database (v1.6a) (Hammond & Jones 2008) in order to highlight if variation exists and to examine issues of choice encountered by life cycle assessment practitioners.

#### ***6.13.11 Modelling the life cycle stages***

Calculating the associated life cycle (LC) emissions for Ormonde Offshore Wind Farm requires finding all of the inputs to the defined system. These LC emissions will be associated with the farm's material and energy resources used throughout its life cycle. This includes the turbines' production, their transport, the construction phase of the farm, the use phase where 508GWh/year is projected to be generated for 20 years and the end of life phase where the farm is dismantled and processed. It should be noted that this is not derived from a theoretical total for production over the full lifetime of the offshore wind farm but based on current yearly output. As will be seen in the section below, if the lifetime of the farm is reduced in reality, the output will be reduced accordingly, based on this yearly output obtained from the farm operator, Vattenfall.

### **6.14 Impact Assessment of critical factors in LCAs**

#### ***6.14.1 Sensitivity Analyses***

This sensitivity analysis has been set up in order to assess a number of possible scenarios for this offshore wind farm as Chapter 5 highlights a sensitivity analysis' importance to better understand variability in estimated wind farm life cycle environmental impacts. This has been done through using two different datasets, the Ecoinvent and ICE databases for estimating the life cycle emissions of system processes



of material production. The lowest and highest estimations of total life cycle emissions from dataset choice are chosen. For end-of-life methodology, the three methodologies set out by Hammond & Jones (2008) recycling are used in order to find minimum and maximum possible total life cycle emissions that can be seen through methodological choice. By using the three methodologies outlined in Section 6.3, further analysis of sensitivity in GHG estimation for Ormonde Offshore wind farm is conducted in relation to methodological choice. This relates to Chapter 5's findings that system boundary and methodological choice are critical factors in LCAs. This is also done *“to better understand the uncertainties in the data or of applying different methodologies during the modelling”* (D'Souza et al. 2011).

#### **6.14.2 Scenario Analyses**

*“Scenario analyses allow the practitioner to assess how the results of the LCA will vary if the model is set up in different ways e.g. representing different possible operating conditions”* (D'Souza et al. 2011).

Lifetime variations from 10 years to 25 years have been used for one of the scenario analyses. This is taking the proposed worse-case scenario for some wind farms from commentators (Hughes 2012b) and also comments from Vattenfall's project manager on when he anticipates a review of Ormonde's effectiveness into its life time. This is to assess the effects of the assumption of project lifetime on total GHG estimates and extends the results from Chapter 5 where lifetime is highlighted as one of the most important factors in an LCA. Capacity factor (CF) variations from 20 - 45% have also been used as a scenario analysis due to Chapter 5's findings in order to assess how a reduction in the power output of Ormonde will affect the farm's ability to reduce associated GHG emissions from grid power. 20% is a lower capacity factor than any current published LCAs (Dolan & Heath 2012) have used for offshore farms so it offers an analysis at the low end of electricity production. 45% CF is used since it relates to the highest values found in the same reference. Lifetime and capacity factor assumptions have significant effects on GHG estimation for the life cycle of wind power as shown in the previous chapter, as well as by Dolan & Heath (2012).

## 6.15 Results

### 6.15.1 Input Data for Ormonde Offshore Wind Farm

The following data was obtained from direct discussions with the operators of Ormonde offshore wind farm. This data forms the basis of the analyses.

<b>Ormonde Offshore Wind Farm</b>	
Area	8.7km <sup>2</sup>
Distance from Shore	9.5-14km
Tidal Range	9m
Number of Rows/Turbines:	2 x 8 turbines, 2 x 7 turbines
Distance Between Rows/Turbines:	760 m / 560 m, 760 m / 560 m
Location:	Barrow-in-Furness
Region:	Cumbria
Country:	United Kingdom
Sea Name:	Irish Sea
Water Depth:	17-21 m
Capacity	150MW
Annual Production Target	508GWh (equal to 38.66% CF)
Turbines	30 x 5MW REPower
Tower	90m
Inter-Array & Export Cables	Prysmian 33kV, Prysmian 132 kV
Substations	1 onshore and 1 offshore
Substructure	31 Jacket Structure with Pile foundation
Cost	552m Euros

**Table 6.7:** Overview of Ormonde Offshore Wind Farm

<b>Turbine Components</b>	<b>GWP (kgCO<sub>2</sub>e)</b>
Transportation and assembly	54,000
Rotor and hub	621,000
Housing, transformer and converter	1,371,000
Tower	951,000
*Gearbox Replacements (0.5 per turbine – 15 per farm)	404,600
*Blade Replacements (1.25 per turbine – 37.5 per farm)	786,700
<b>TOTAL FOR FARM</b>	<b>4,188,300</b>

**Table 6.8:** Associated life cycle GHG emissions for REPower 5M Turbine (Wagner et al. 2011) with additional replacement parts data\* (D'Souza et al. 2011).

<i>Component</i>	<i>Material</i>	<i>Weight (kg)</i>	<i>GHG Intensity Factor (kgCO<sub>2</sub>e/kg)</i>		<i>TOTAL GHG Emissions (kgCO<sub>2</sub>e)</i>	
			<b>ICE</b>	<b>Eco-invent</b>	<b>ICE</b>	<b>Eco-invent</b>
Inter-Array Cables	Copper	139,308	2.71	3.14	377,525	437,427
	Steel	116,772	1.46	1.75	170,487	204,351
	Thermoplastics	173,526	3.31	1.94	574,372	336,641
	Ceramic/Glass	1,274	0.91	1.09	1,159	1,388
Export Cable	Copper	703,800	2.71	3.14	1,907,298	2,209,932
	Steel	420,638	1.46	1.75	614,132	736,117
	Thermoplastics	1,199,015	3.31	1.94	3,968,738	2,326,088
	Ceramic/Glass	2,752	0.91	1.09	2,505	3,000
Cable Protection System	Steel	44,799	1.54	1.75	68,991	78,398
	Thermoplastics	52,191	4.26	4.25	222,334	221,812
Jackets and Boat Landings Piles	Steel	15,500,000	1.46	1.75	22,630,000	27,125,000
	Steel	8,000,000	1.46	1.75	11,680,000	14,000,000
Grouting	Cement	1,894,820	0.95	0.82	1,800,079	1,553,752
Substation	Steel	3,500	1.46	1.75	5,110	6,125

**Table 6.9:** Material Inventory and total associate GHG emissions for Ormonde Offshore Wind Farm’s additional infrastructure using ICE and Ecoinvent databases (REPower turbines not included)

<i>Component</i>	<i>From</i>	<i>To</i>	<i>Distance by Sea (nautical miles)</i>	<i>Component Weight (t)</i>	<i>Total Weight (t)</i>	<i>tkm</i>	<i>kgCO<sub>2</sub>e</i>
Nacelles	Bremerhaven, Germany	Belfast H&W	837	315	9,450	7,909,650	366,217
Blades	Aalborg, Denmark	Belfast H&W	872	19.5	1,755	1,530,360	70,856
Tower	Cuxhaven, Germany	Belfast H&W	824	221	6,630	5,463,120	252,942
Substation	Barrow-in-Furness	Site	5.4	895	895	4,833	224
Stored Components	Belfast H&W	Site	116	555.5	17,835	2,068,860	95,788
Foundations	Methil, Scotland	Site	616	500	15,500	9,548,000	442,072
						<b>TOTAL</b>	<b>1,228,099</b>

**Table 6.10:** Transport associated with component delivery to Ormonde Offshore Wind Farm. Conversion factor used = 0.0463 kgCO<sub>2</sub>e/tkm (Defra/DECC 2013a).

<i>Vessel Use</i>	<i>Marine Diesel Use (litres)</i>	<i>GHG Emissions (kgCO<sub>2</sub>e)</i>
Construction	478,340	1463481
Operations and Maintenance *	480,000	1468560
Decommissioning	478,340	1463481
<b>TOTAL</b>	<b>1,436,680</b>	<b>4,395,522</b>

**Table 6.11:** Transport associated with construction, operations and maintenance, and decommissioning of Ormonde Offshore Wind Farm. Conversion factor used = 3.0595kgCO<sub>2</sub>e/litre marine fuel use (Defra/DECC 2013a).

\* (average 60 trips to wind farm per year – 400 litres fuel use per trip)

<i>Recycling of Major Components</i>	<i>ICE (kgCO<sub>2</sub>e)</i>	<i>Ecoinvent (kgCO<sub>2</sub>e)</i>
Recycling net benefit	-25,446,314	-22,111,932
Impacts of disposal* and reprocessing**	798,257	798,257
<b>TOTAL</b>	<b>-24,648,057</b>	<b>-21,313,675</b>

**Table 6.12:** Recycling Impacts associated with processing major components and associated materials

\* landfilling and incineration – thermoplastics and remaining scrap steel - incineration of polypropylene = 2.54 kgCO<sub>2</sub>e/kg, steel to landfill = 0.00709kgCO<sub>2</sub>e/kg

\*\* recycling practises (Ecoinvent) – steel recycling = 0.814kgCO<sub>2</sub>e/kg,

Table 6.12 has been used in conjunction with Table 6.6 to determine total amounts of recycled materials from the turbines and associated infrastructure.

### 6.15.2 Process-Based Analysis

The following results were found for Ormonde Offshore Wind Farm using a process-based analysis explained in Section 6.3.1.

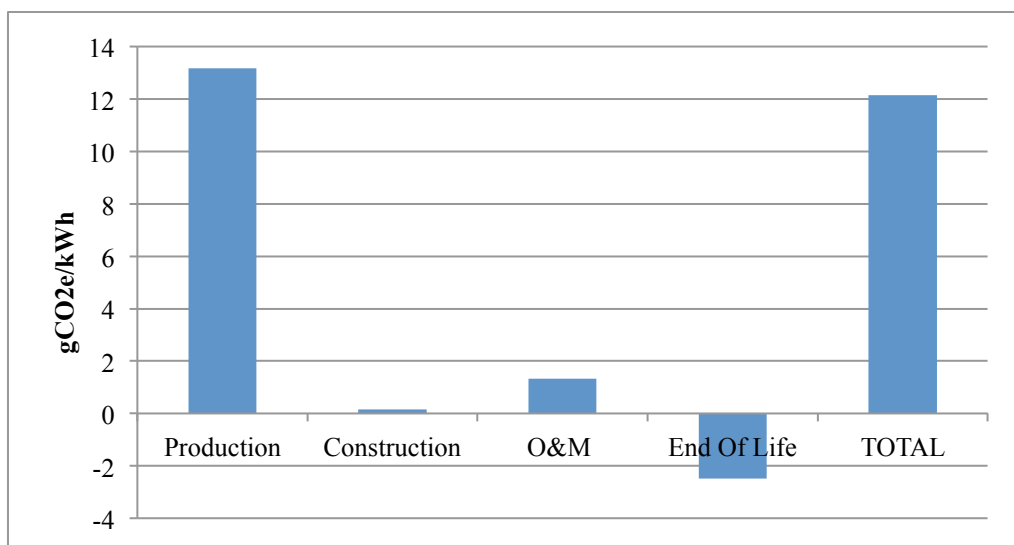
<i>Life Cycle Phase</i>	<i>ICE (kgCO<sub>2e</sub>)</i>	<i>Ecoinvent (kgCO<sub>2e</sub>)</i>	<i>GHG Intensity (gCO<sub>2e</sub>/kWh) (ICE)</i>	<i>GHG Intensity (gCO<sub>2e</sub>/kWh) (Ecoinvent)</i>
Production	133,932,728	139,150,032	13.2	13.70
Construction	1,463,481	1,463,481	0.14	0.14
O&M	13,381,635	13,381,635	1.32	1.32
End Of Life	* -25,354,635	** -20,648,450	-2.36	-2.03
<b>TOTAL</b>	<b>123,423,210</b>	<b>133,346,698</b>	<b>12.28</b>	<b>13.12</b>

**Table 6.13:** Life Cycle Phases and Total GHG estimates for Ormonde Offshore Wind Farm from process-based analysis (kgCO<sub>2e</sub>)

\*using ICE database's recommended *recycled content* method.

\*\*using Ecoinvent's factor for steel recycling as outlined in Section 6.13.3

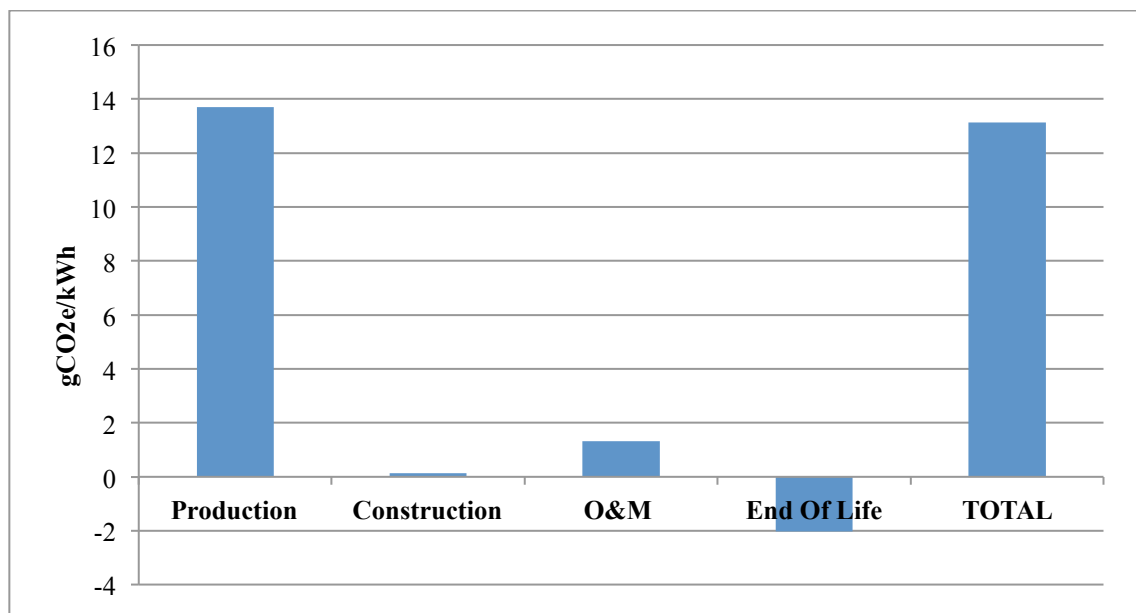
It should be noted that due to the assumptions made and availability of data, the dataset choice between the ICE dataset and Ecoinvent only affects the *production* and *end of life* phases of this wind farm. The difference between these two estimates is 3.8% which can be seen to be not overly critical and as previously seen in Chapter 5, dataset choice is not a critical factor in the estimation of associated life cycle GHG emissions of wind farms.



**Figure 6.4:** Life Cycle GHG Emissions for Ormonde Offshore Wind Farm from process-based analysis using ICE database and recycled content method

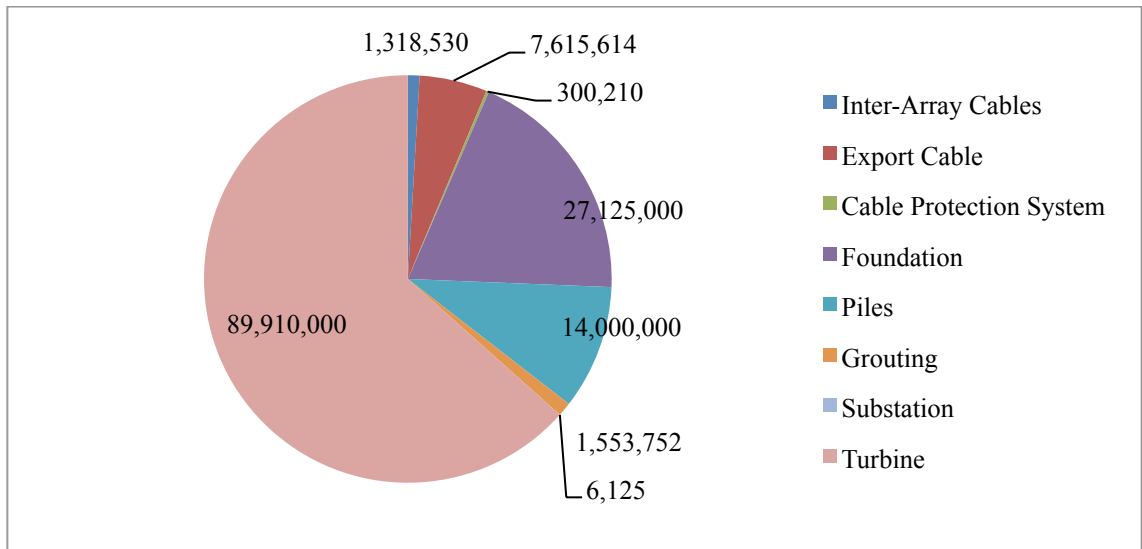
The following Figures 6.4 and 6.5 show the Ecoinvent database results and since this is the most widely used database, the Ecoinvent database results will be utilised for the novel hybrid analysis. The process-based analysis using the Ecoinvent database can be said to be conservative relative to the ICE database due to its estimate being larger.

Figure 6.4 shows the contributions from each life cycle phase of Ormonde Offshore Wind Farm. It clearly shows life cycle GHG emissions associate with production to be the largest contributor to total emissions. A small relative benefit of recycling is seen as a negative value in relation to a reduction in total associated GHG emissions.



**Figure 6.5:** Life Cycle GHG Emissions for Ormonde Offshore Wind Farm from process-based analysis using Ecoinvent dataset

Figure 6.5 shows the contributions from individual parts of major components of the wind farm. It can be seen that the turbine dominates contributions, with foundations being the second largest contributor to total GHG emissions associated with production of components.



**Figure 6.6:** Relative contribution of individual elements of the wind farm to total life cycle GHG emissions (kgCO<sub>2</sub>e) from the production phase of Ormonde Offshore wind Farm

### 6.15.3 Cost-Based Analysis

The following results were found for Ormonde Offshore Wind Farm using the cost-based analysis explained in Section 6.3.2. Cost data is from the cost breakdown for a typical offshore wind farm in the UK (RAB 2010). Embodied GHG emissions in the second column from the left in Table 6.14 are from the process-based analysis above. GHG intensity is found by dividing embodied GHG emissions by the total costs. Production and construction is considered together since the cost breakdown information is for CAPEX, which includes both production and construction activities. Please see cost breakdown for the Offshore Wind Farm's Project Stages for CAPEX (Figure 6.1) and OPEX (Figure 6.2). The OPEX is given as a range of €17-20/MWh and this analysis only uses the highest figure of €20/MWh for operations and maintenance in order to be conservative.

<i>Life Cycle Phase</i>	<i>Embodied GHG Emissions (kgCO<sub>2</sub>e)</i>	<i>Cost (Euros - €)</i>	<i>GHG Intensity (kgCO<sub>2</sub>e/€)</i>
Production	139,150,032	408,480,000	0.2547
Construction	1,463,481	143,520,000	0.2547
O&M	13,381,635	187,584,080	0.0713
Decommissioning	-20,648,450	125,304,000	-0.1648

**Table 6.14:** Life Cycle Phases and Total GHG estimates for Ormonde Offshore Wind Farm from cost-based analysis (kgCO<sub>2</sub>e)

#### 6.15.4 Novel Hybrid Analysis

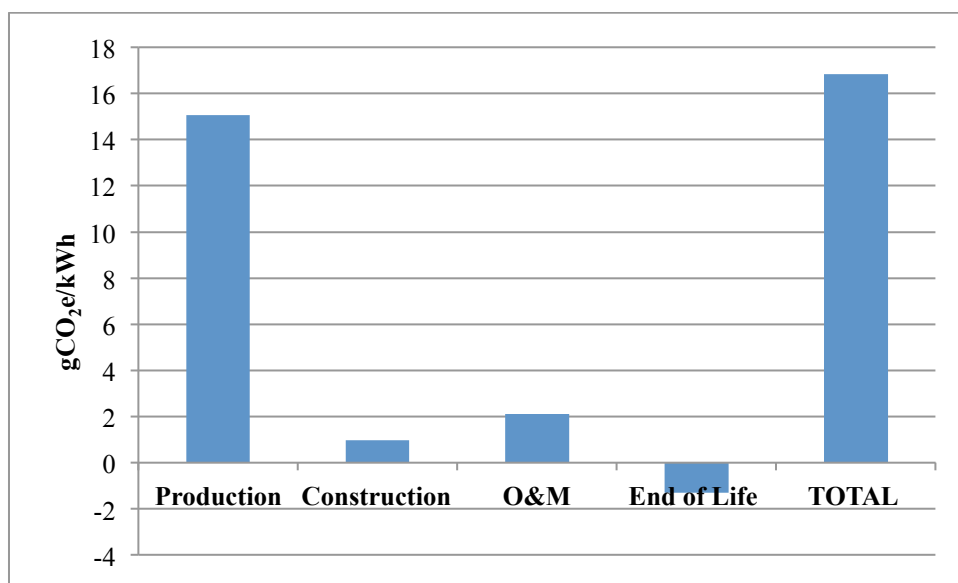
The following results were found for Ormonde Offshore Wind Farm using the novel hybrid analysis explained in Section 6.3.3. Please see cost breakdown for the Offshore Wind Farm’s Project Stages for CAPEX (Figure 6.1) and OPEX (Figure 6.2).

It is estimated that the life cycle activities not included in the process-based analysis account for 43% of economic costs of this offshore wind farm’s CAPEX. Additionally, 59.9% of economic costs relating to operations and maintenance are also not included in the process-based analysis. These data gaps represent the additional life cycle environmental impacts in this novel hybrid analysis that can be accounted for when using the combination of process and cost-based information. Using the ratios presented in table 6.3, those life cycle activities that are identified as not being included in the process-based analysis (those greyed out in the cost breakdown figures 6.1 and 6.2) are now included by utilising the GHG intensity factor for that given life cycle phase and the economic cost associated with that activity. These missing activities equate to €236,500,000 and €121,470,000 for CAPEX and OPEX activities respectively for Ormonde Offshore wind farm.

<i>Life Cycle Phase</i>	<i>Embodied GHG Emissions (kgCO<sub>2</sub>e)</i>	<i>GHG Intensity (gCO<sub>2</sub>e/kWh)</i>
Production	158,920,292	15.64
Construction	10,237,764	1.01
O&M	21,397,234	2.11
End Of Life	-12,987,826	-1.28
<b>TOTAL</b>	<b>177,567,465</b>	<b>17.48</b>

**Table 6.15:** Life Cycle Phases and Total GHG estimates for Ormonde Offshore Wind Farm from novel hybrid analysis (kgCO<sub>2</sub>e/kWh)





**Figure 6.6:** Life Cycle GHG Emissions for Ormonde Offshore Wind Farm from novel hybrid analysis

It can be seen that when comparing the results from the process-based analysis and the novel hybrid analysis above, a number of data gaps can be outlined and quantified, based on the methodology proposed by this chapter. The following points highlight important outcomes from using this hybrid approach.

- Process-based analysis is not capable of quantifying activities such as development and consent of a wind farm, impacts associated with labour and also those from other activities such vessel and crane services, insurance and other overheads not directly associated with materials / products
- Based on this analysis, 19% of impacts associated with the ‘*production*’ life cycle phase have not been accounted for in the process-based analysis.
- 24% of impacts associated with the ‘*construction*’ life cycle phase have not been accounted for in the process-based analysis
- Nearly 60% of impacts associated with the ‘*operations and maintenance*’ life cycle phase have not been accounted for in the process-based analysis
- Overall benefits from end of life recycling (or equivalent economic benefit of selling turbines at the end of the farm’s operational life) are reduced in this hybrid analysis due to previously missed activities of labour and vessel and crane use in decommissioning that can be included in this hybrid approach.

- Overall, there is a 25% increase in life cycle GHG emissions when using this hybrid approach when compared with process-based analysis.

### 6.15.5 Sensitivity and Scenario Analyses

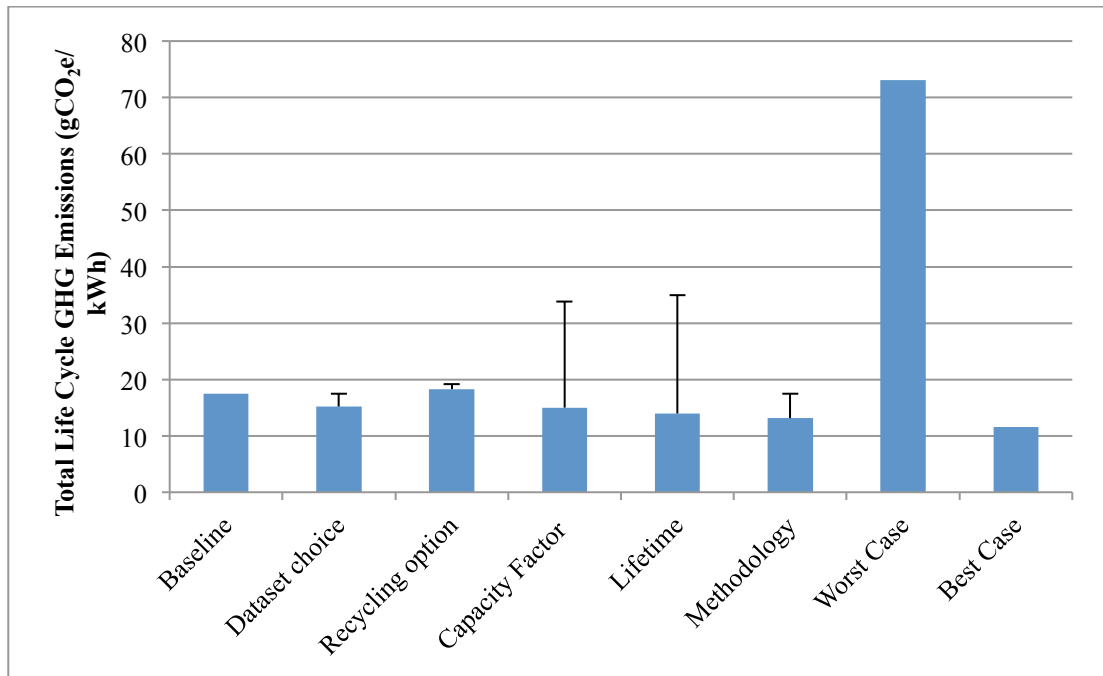
The following ranges of results in Table 6.16 were found from the sensitivity and scenario analyses outlined in Section 6.14. These scenarios relate to the baseline life cycle assessment using the novel hybrid analysis results in Section 6.15.4.

Figure 6.8 shows the results from these sensitivity and scenario analyses and presents bars for each to show the possible ranges of results, as shown in Table 6.16 numerically. Worst and best case scenarios present the combination of highest and lowest estimates for total life cycle GHG emissions respectively when considering all choices made by an assessor throughout the analysis process.

<b>Scenario/ Sensitivity</b>	<b>Dataset choice (ICE/ Ecoinvent)</b>	<b>Recycling (Yes/No)</b>	<b>Capacity Factor (%)</b>	<b>Lifetime (years)</b>	<b>Method -ology</b>	<b>Total Life Cycle Emissions (gCO<sub>2e</sub>/kWh)</b>
<b>Baseline</b>	Ecoinvent	Y	38.7	20	Hybrid	<b>17.48</b>
<b>Dataset choice</b>	ICE / Ecoinvent	Y *	38.7	20	Hybrid	<b>15.21 – 17.48</b>
<b>Recycling only</b>	Ecoinvent	Y & N	38.7	20	Hybrid	<b>18.3</b>
<b>Capacity Factor</b>	Ecoinvent	Y	20-45	<b>20</b>	Hybrid	<b>33.8 – 15.01</b>
<b>Lifetime only</b>	Ecoinvent	Y	38.7	<b>10-25</b>	Hybrid	<b>34.95 – 13.98</b>
<b>Method- ology</b>	Ecoinvent	Y	38.7	<b>20</b>	Process- based / Hybrid	<b>13.12 - 17.48</b>
<b>Worst Case</b>	Ecoinvent	N	20%	10	Process- based	<b>73.07</b>
<b>Best Case</b>	ICE	Y	45%	25	Hybrid	<b>11.57</b>

**Table 6.16:** Range of GHG estimates for Ormonde Offshore Wind Farm from sensitivity and scenario analyses

\*Recycled Content Method of recycling method suggested by the ICE Database for metals and used in this scenario (Hammond & Jones 2008)



**Figure 6.8:** Effects to total life cycle GHG estimates from different scenarios (Lifetime, capacity factor) and sensitivity analyses (recycling, dataset and methodology choice) for Ormonde Offshore Wind Farm

## 6.16 Discussion of Results

It can be seen from the results that critical factors such as the assumed lifetime or the capacity factor of a wind farm have a very significant impact on a life cycle assessment. The results found in this chapter are all within the range of published life cycle estimates for offshore wind farms.

### 6.16.1 Methodological Choice

The process-based analysis presented here gives total associated life cycle GHG emissions of 13.1gCO<sub>2</sub>e/kWh. This is comparably low when compared to those historic life cycle GHG emissions estimates from historic wind farm LCAs and especially of offshore wind farm sites. However, this is explained by the lack of certain data as already mentioned, in particular 19% of impacts associated with the ‘*production*’ life cycle phase have not been accounted for in the process-based analysis. Also, 24% of impacts associated with the ‘*construction*’ life cycle phase have not been accounted for in the process-based analysis and nearly 60% of impacts associated with the ‘*operations and maintenance*’ life cycle phase have not been accounted for in the process-based analysis.

The novel hybrid analysis presented here gives total associated life cycle GHG emissions of 17.5gCO<sub>2</sub>e/kWh. This is comparable with the average for harmonised global historic offshore wind farm estimates of 18.2gCO<sub>2</sub>e/kWh. This similarity appears to support this hybrid approach. However, it is clear those critical factors such as the lifetime and capacity factor of the wind farm have a large impact on overall GHG emissions estimates. Conversely, it can be seen that while varying sensitivities of dataset choice, methodological choice and recycling options have a significant effect, they are much less critical and do not dramatically change the range of possible life cycle GHG emissions estimates.

### **6.16.2 Dataset Choice**

While simply looking at the production life cycle phase suggests dataset choice only affects results by a small amount (3.8% of total embodied emissions in the process-based analysis), once the full life cycle is considered and conducted in this case as a hybrid analysis, the dataset choice between Ecoinvent and the ICE database gives a difference of 13% in total life cycle emissions. This equates to 2.3 gCO<sub>2</sub>e/kWh overall. This all considers different recycling allocation since the ICE database suggests the recycled content method. This is the only sensitivity analysis that has two variations but it was deemed necessary because of the ICE database's suggestion to use the '*recycled content method*' (Hammond & Jones 2008) for metal recycling, which is predominant in this case.

### **6.16.3 Effects of Recycling**

By either conducting recycling or not (as well as the total estimated life cycle GHG emissions range based on cost-based analysis that gives likely economic benefits of being able to sell capital assets), the total estimated life cycle GHG emissions for this case increase by 0.82gCO<sub>2</sub>e/kWh (4.7%). This is in line with the harmonisation results from Chapter 5 that also show how recycling has a significant but small effect on total estimated life cycle GHG emissions. It should be mentioned that it is highly unlikely that no recycling will be conducted on such a project. However, due to a lack of real offshore wind farm projects entering the decommissioning phase, current practices are unknown and this analysis offers a suggestion into the benefits of conducting such recycling.

#### ***6.16.4 Capacity Factor***

The range of 20-45% was used for possible capacity factors for this offshore wind farm. These have significant effects on the estimation of total life cycle GHG emissions and produce a range of 15.0 – 33.8gCO<sub>2</sub>e/kWh. The baseline figure for this case study is 17.5gCO<sub>2</sub>e/kWh, which is close to the lower estimate in this instance. This is because the capacity factor obtained from the operator Vattenfall was 38.7% and is close to the upper limit of suggested capacity factors. It can be seen that nearly halving the capacity factor to 20% has the adverse effect of nearly doubling the total life cycle GHG emissions associated with the farm as would be expected as the total generation is halved. This appears to be logical and highlights how important it is for a wind farm to operate at a high capacity factor. Since this is an offshore wind farm in one of the windiest parts of the UK, the figure for the baseline does not seem entirely unreasonable and suggests that the lower limit of total life cycle GHG emissions in this instance could be not be considered too unreasonable.

#### ***6.16.5 Lifetime***

As described, there is potential for a wind farm to have a much lower operational life than initially intended. The analysis presented shows lifetime varying from 10 – 25 years, based on previous discussion and gives a range of 14.0 – 35.0gCO<sub>2</sub>e/kWh total life cycle GHG emissions. Effectively, halving the age of the wind farm's operational life produces double the total life cycle GHG emissions associated with its electricity. This is intuitive but also highlights how important it is for the wind farm to remain productive for a guaranteed period of its life. However, it seems unlikely that a wind farm would be stopped from efficiently producing electricity after 10 years unless there were serious technological problems. Vattenfall have mentioned that they are contractually obligated by the network operators, Nation Grid to offer availability of their wind turbines of 98% for the duration of the lifetime of the project so it is in their interest to ensure this is the case, albeit there might be cost implications for the operation and maintenance of the farm for this to occur. Indeed, they have suggested that ideally, the turbines would be replaced on a given wind farm once the 20 years design life had passed in order to continue to use the offshore infrastructure in place and utilise newer, more efficient machines. Also, anecdotally, current thermal power stations in the UK tend to have their licences to produce electricity extended, provided they are operating suitably, due to relative costs of refurbishing old stations versus building new ones. Coal power stations in the UK, as seen in Chapter 3 are considerably

older than their intended design lives. It seems reasonable in this case to assume that wind farms would not be treated differently so perhaps another analysis is required to see what would happen if new turbines were installed on an existing offshore grid network and a secondary life cycle take place.

#### ***6.16.6 Methodology***

By using cost-based data to suggest the novel hybrid analysis of Ormonde Offshore Wind Farm, an estimated additional 4.36gCO<sub>2</sub>e/kWh is attributed to Ormonde Offshore Wind Farm that would not otherwise have been considered. This highlights the difficulty with using process-based analysis alone to estimate total life cycle GHG emissions since it cannot account for items such as labour, vessel and crane use (that is not only fuel use), port activities and preliminary work such as development and consent. While this analysis cannot guarantee the accuracy of specific estimation for these activities, by including cost-based information, greater coverage of all activities associated with the wind farm is achieved, enabling the assessor to have a greater understanding of the life cycle phases involved in offshore wind farms. While these activities may have relatively low associated life cycle emissions, they are simply not included in a process-based analysis and this highlights the differences in approach. It is recommended that the hybrid analysis used in this case study be adopted for future offshore wind farms in order to provide more complete assessment.

#### ***6.16.7 Case Study Range***

The total range of results from this analysis is 11.6 – 73.1gCO<sub>2</sub>e/kWh. The worst-case scenario (highest life cycle GHG emissions) is six times larger than that of the best-case scenario (lowest life cycle GHG emissions). This represents an extreme range in possible estimates for total life cycle GHG emissions and highlights sensitivities in results. However, it can be clearly seen through singling out each scenario and sensitivity analysis that this range is predominantly due to changes in capacity factor and lifetime. Indeed, the worst-case scenario, as shown in Table 6.16 and Figure 6.8, represents a very low capacity factor for offshore wind of 20% over a 10-year lifespan. It could be said, however, that based on this likely range of worst to best-case scenario, that this estimate is relatively low to possible outcomes and could be considered optimistic. However, due to the open nature of this estimation procedure, this can be discussed and justified as laid out.

Even with these conditions, wind power is still very favourable when compared with the life cycle GHG emissions from both gas and coal power stations which are approx. 500gCO<sub>2</sub>e/kWh and 1000gCO<sub>2</sub>e/kWh respectively as shown in Figure 3.14; NREL (2012). Even very low estimates for traditional technologies do not offer estimated life cycle GHG emissions as low as offshore wind power in this instance. Possible ranges for nuclear power from the average of 66gCO<sub>2</sub>e/kWh (Sovacool 2008) and those found by NREL (2012) for nuclear power are within a similar range and, it could be argued, are much less subject to uncertainty over probable lifetimes.

### **6.17 Conclusions**

The true total life cycle GHG emissions that can be attributed to the Ormonde Offshore wind farm project will likely lie within the results given above. It is impossible to know exactly what this answer is but by highlighting the various issues in estimating this figure, it can be seen that some assumptions made by the assessor are more important than others. These will become ever more apparent as more life cycle studies are published but through a harmonisation study in Chapter 5 and this chapter's case study, it can be clearly seen that hybrid analyses, while offering the highest estimates, also include far more of the project's stages than either the process or cost-based analyses. While this is intuitive, it should also be seen that the perceived complexity of hybrid analyses could be reduced through further research into cost breakdowns of wind farms and the allocation of these costs across the lifetime of a wind farm. Decision-makers should be wary of any life cycle estimate that does not make it clear which critical factors (predominantly capacity factor and lifetime) are chosen and why, along with methodological choices for recycling and dataset choices. The clearer the life cycle study is on the critical factors it assumes, the easier it is for a decision-maker to see the possible range on which to base future decisions.

An important element of this life cycle study is lacking. This is the likely effects of wind farms on a power system such as that in the UK where traditional plants are also contributing to total generation and the dynamics of their interaction. This will be discussed in the following chapter in order to attempt to assess whether intermittent power generation has a detrimental effect on the efficiencies of the traditional power plant fleet.

## **Chapter 7 – Wind Power Interaction in Electricity Networks**

Wind power has seen large, subsidised growth across the EU in recent years. While being a low carbon form of power, wind generation is an intermittent source and may be causing a detrimental effect to the thermal generation fleet in the current electricity networks due to a number of factors. The following chapter aims to assess the extent to which thermal plants increase their carbon intensity per rated output as a result of operating at reduced output and experiencing greater cycling in response to changes in wind power variation.

In this chapter, two approaches are taken to assess these changes. Firstly, efficiencies of both coal and gas plant are calculated using published fuel use data in conjunction with total generation over a period of 3 years (July 2009 – June 2012) in relation to wind power's contribution to total generation. Secondly, variability in the supply of wind power is assessed in relation to its effects on residual load factors felt by thermal power plants in the UK and the resulting increase in carbon intensity relative to rated output for 2 years (January 2013 to December 2014) is calculated. It is demonstrated that there are definite effects felt by the thermal plants on the UK network. While wind power's output profile may not be directly attributable to observed efficiency changes, a reduction in residual load factor of the thermal fleet is clearly increasing carbon intensity relative to rated output in certain instances. Greater work is needed in further understanding the factors influencing an increase in carbon intensity for UK electricity as a result of balancing the electricity supply network with increasing levels of installed intermittent sources of power.

### **7.1 Introduction**

Electricity policy exists in most countries to ensure the following three important criteria are met: security of supply, protecting environmental quality and economic efficiency. In recent years, the balance has lent towards protecting environmental quality due to EU directives and individual states imposing their own regulations in response to this. Some would argue this has jeopardised the other two criteria since strong emphasis has been placed on renewable technologies that have reduced the contributions of conventional plant in matching demand causing both financial inequality in the electricity markets and subsidies such as ROCs in the UK creating negative pricing for long periods or very high prices at other times (Moreno &



Martínez-Val 2011). Also, while the EU directives and individual state policies have helped towards renewable production targets (and carbon reduction targets), they may have also caused inefficient dispatch of generation from conventional plant, as renewable generation has constrained otherwise optimal unit commitments of conventional plant (Perez-Arriaga & Batlle 2012).

Wind power has seen large growth across the EU now for 25 years. Countries such as Spain have seen dramatic increases in wind generation, with 2009 seeing 13.6% gross generation (Moreno & Martínez-Val 2011). This deployment has largely been due to the rate of growth of combined cycle gas turbine (CCGT) plants that are able to increase power output at a relatively fast speed (if over their rated minimum power) and can cope with the reported large fluctuations in output from wind power. These have seen declines in power output from wind power of 10GW in less than a day, increases of 16GW in 8 hours and a maximum power rise of 8GW in under 5 hours (Moreno & Martínez-Val 2011).

### ***7.1.1 Issues of wind power entering an electricity supply network***

The effects associated with increased penetration of renewable technologies (in particular wind) on conventional thermal plants in current electricity supply systems have been reported in a number of key areas. This section aims to cover the main areas where these thermal plants are operating in different regimes to their originally designed activities. To understand this, it should be realised that the thermal plant element of an electricity supply network has to cope with new, intermittent technologies generating power since the other major generation element of nuclear power in the UK situation operates almost exclusively for the supply of base-load power. The conventional plants are therefore responsible for the majority of operations of regulation on the system to ensure it delivers electricity when required. It is also not simply a matter of estimating the total annual production but to know the probability of reaching peak values since hourly demand characteristics will be as important to maximum peak demands in planning for a secure electricity supply. Results from the Spanish system have suggested the estimated projections of the generation system show that the required back-up power will grow about 8–9GW by year 2020, in order to maintain security of supply once a share of 40% renewable electricity is achieved (Moreno & Martínez-Val 2011). Thermal plants, in particular coal plants, are shifting from a situation of supplying base load power to supply back up power. This needs to be assessed on

numerous levels such as environmental factors and carbon intensity changes, investment and economic fluctuations so that policy makers and electricity authorities better understand this shift in power generation characteristics.

Wind power's generation is considered intermittent. Intermittency in this case relates to the non-controllable variability and partial unpredictability of this power output (Moreno & Martínez-Val 2011). Since only very near-term predictions of wind output are highly accurate, single plant forecast errors of 5-7% have been suggested in a 1-2 hour timeframe, while 24 hours ahead, these errors can be closer to 20% (Milligan et al. 2009). Improvements in prediction will improve this situation and require better models and more observation data available to the electricity supply network operators. If scheduling intervals are reduced through for example a reduction in market pricing timeframes, it will help reduce the forecast errors of wind that affect operating reserves (Perez-Arriaga & Batlle 2012). The impact of errors occurs in the prediction of output of wind on a day-ahead scheduling of plant since it requires having significant capacity of flexible generation ready with relatively short start-up and/or fast ramping capabilities ready (for example CCGT and OCGT plant) to provide load following and supply reserves (Perez-Arriaga & Batlle 2012).

Wind power alters the shape of the net load to be satisfied with the conventional thermal plant, changing the traditional way of scheduling the thermal portfolio. Peaks of thermal production may no longer happen when the demand is highest. In addition, wind power production results in low value of net demand (for example at night) that can force thermal units to shut down only to have to start up a few hours later (Perez-Arriaga & Batlle 2012). Alternatively grid operators may pay wind generators to stop generating. Cycling refers to changing the operating modes of thermal plant that occur due to varying dispatch requirements such as on/off operation, low-load cycling operations and load following. There are significant maintenance and operational costs associated with these fluctuations (Moreno & Martínez-Val 2011) as well as overall efficiency decreases. This will lead to an increase in carbon emissions, relative to output, from the conventional plants, which must be associated with the intermittent power causing these altered operations. It has been presented that cycling typical coal or gas (CCGT) plants over one hour from 100% output to 80% and then ramping back to 100% actually equates to an increase in fuel use in reality of 1.2% (coal) or 1% (CCGT) as opposed to a perceived reduction in fuel use at the plant due to a reduction in output (le Pair 2011).

This is not commonly discussed and will be quantified through an assessment of UK plant efficiency in relation to fuel use in Section 3.1 since this increase in fuel use per unit output should become apparent from historic data as installed capacity of wind power has increased. Indeed, the article (le Pair 2011) accounts for other factors discussed here such as low thermal efficiency at low power output, life cycle energy of wind turbines, cabling and net adaptation, and the potential increased use of Open Cycle Gas Turbines (OCGT) that will influence total associated GHG emissions as a result of increased wind power in the electricity network. It is suggested by the article, and others (Hughes 2012b; Udo 2011; BENTEK Energy 2010) for the UK, Irish and Colorado systems respectively that wind power does indeed lead to a net increase in GHG emissions for an electricity network relative to those systems without wind power contributions due to the discussed factors. Once cycling and ramping are included in an assessment of wind power's carbon reduction potential, a 12% wind penetration such as that found in the Irish system could lead to only a 4% CO<sub>2</sub> reduction (Udo 2011). This implies that measured CO<sub>2</sub> reduction is (4/12) 33% of the value generally quoted. Udo (2011) discusses how curtailment of wind of less than 20% will lead to an additional 1% increase in CO<sub>2</sub> intensity of grid power and that increasing the penetration of wind energy beyond 10% will have a negligible effect on fuel consumption of the total system, as long as that system has negligible energy storage. Any attempt to reduce curtailment through greater use of wind generation, such as the HVDC links between Scotland and England, will result in lower gas use for electricity generation and lower operating costs (Gerber et al. 2012). It may be "perfectly reasonable to argue that adding wind generation to an electricity system may increase the level of CO<sub>2</sub> emissions relative to its initial level" (Hughes 2012b). Hughes (2012) presents scenarios whereby wind power replaces different merit-order plant and causes overall CO<sub>2</sub> emissions fluctuations ranging from a relatively high increase (replacing base-load generation) to only a very small reduction of overall emissions when replacing peak-load generation. If indeed, wind power does reduce the security of our electricity network, is also more expensive (Bowie 2012) and in fact *increases* CO<sub>2</sub> emissions, then it is at odds with energy policy.

National Grid (2012a) quantified wind generation impacts on carbon intensity in relation to volume of gas used by generators compared with the amount of electricity generated over time (which captures fuel use associated with cycling and ramping) as well as calculation of indirect carbon emissions arising from forecast errors. The

National Grid study's method would capture the most important factors, as per another study by Le Pair (2011) and yet come to a dramatically different conclusion that overall reduction of benefit to the carbon intensity of wind power is 0.081%. This would still suggest a large benefit of wind power in reducing overall carbon intensity of UK electricity. What is apparent in all assessments of this issue is that variations in power station efficiency may be due to a range of reasons, not just those associated with intermittent wind, such as age of plant, temperature, maintenance schedules and operating strategy and other market forces. It is seen as very difficult to link the variations of efficiency of gas fired power stations directly to wind intermittency (National Grid 2012a). Simply put, not enough has been done to account for the variety of factors influencing the carbon intensity of power from a network containing wind (and other intermittent sources) to fully account for the factors surrounding wind power integration. Few would dispute that without significant investment in balancing technologies and frameworks associated with these, the task of ensuring all energy policy elements are met will be very difficult, due to the large penetration of renewable technologies (Strbac et al, 2012). It is estimated by Goodall & Lynas (2012) that wind power in the UK in 2012 reduced the overall GHG emissions from electricity production by 4% and that sceptics are not looking at evidence coming from production data and also that as weather prediction improves, the National Grid will be able to plan the right generation mix to meet demand a day in advance, resulting in less short-term cycling than predicted. Perhaps, the real threat is still from single unexpected large outages of power plants rather than the newer intermittent technologies entering the generation portfolio (Goodall & Lynas 2012).

Another issue that may occur due to the residual electricity demands left by large penetrations of wind that thermal plant, mainly gas power stations will be responding to, is a possible gas supply constraint through the gas supply network. Increased storage of gas would invariably be required to deal with CCGT plant operating at reduced capacity with large fluctuations in their output over a short time period (Qadrdan et al, 2010). This is also further elaborated on by PE Consulting (2009) who suggest that gas markets of a region will become ever more dependent upon that region's weather once intermittent power sources are included. This again highlights the importance of forecasting in relation to electricity supply.

The most critical factors for the stability of power systems are the mechanical inertia provided by the rotating mass of all turbines on the system and the system's capability to work outside the scheduled variations i.e. react to those variations that were not anticipated (Perez-Arriaga & Batlle 2012). Wind can act positively in this with voltage controls, power ramping and curtailment and a variety of other controls (Perez-Arriaga & Batlle 2012), but it is also the main cause for this requirement, along with other intermittent sources of power. Due to a large penetration of renewable technologies now seen on the Spanish grid, gas turbines may be operating in cyclic conditions where the load at off-peak time (low demand) can be as low as 40-50% of the base-load and the number of start-ups double those that would occur without the installed renewables (Perez-Arriaga & Batlle 2012).

In thermal systems, renewable generation implies a very significant change in the scheduling regimes of the rest of the generation facilities. While this makes variable costs of fuel generally decrease, other extra running costs are derived from frequent cycling in the operation of thermal units (Perez-Arriaga & Batlle 2012).

The nature of merit-order effects on a system is critical. If CCGT technology is the setter of marginal prices in most hours of a day, then wind has less impact on reducing the total cost of electricity since it does not change the marginal technology, i.e. the CCGT plant. As seen in Spain, the lower electricity price drops can be better explained due to a reduction of CCGT load factors and activation of inflexible take-or-pay clauses in supply contracts (Perez-Arriaga & Batlle 2012), such as those found in the UK through the Renewables Obligation (RO). This obscures the subsidy payments to wind operators.

While CCGT plants are flexible, have short construction times relative to other plant and low specific investment costs, they also will be working a shorter number of hours making investment recovery more difficult and their variable costs are highly dependent on the gas price. There will also be an increased number of start-ups that lower efficiency, result in more maintenance and reduce the lifetime of the plants. While Gas-fired generation is considered as the main technology that can react to intermittency due to shorter start-up times than coal power plants (Parsons Brinckerhoff 2009), there are still options on the technology. CCGT plant are often quoted to predominantly do this, especially as seen in Spain (Moreno & Martínez-Val 2011), OCGT has also been

suggested to be used, especially due to the nature of CCGT plant being inefficient if it is not hot enough to produce steam. If CCGT plant are still used in fluctuating periods and are running less efficiently, they may burn 50% more fuel per MWh (thus 50% more CO<sub>2</sub> per MWh) (Bowie 2012). An even greater problem will be if coal plants are also cycled in response to wind intermittency. Coal plants are specifically not designed to be cycled and so they are less efficient when operated to do so, leading to emissions increases of all major GHG gases and other polluting emissions. This problem would also persist for perhaps a day after cycling (BENTEK Energy 2010). Since in the UK, the Large Combustion Plant Directive (LCPD) will retire 12GW of coal and oil-fired capacity (National Grid 2012b), this may not be too much of an issue in the UK, but it is still an important consideration in system-wide effects of wind intermittency.

The carbon permit price and other similar financial agreements that have been agreed by EU countries have had no effect on the electricity price in those countries. This has been the case in the UK, Greece, Germany, Italy and Spain especially, where renewable technologies now represent a significant share of total electricity generation (Moreno & Martínez-Val 2011).

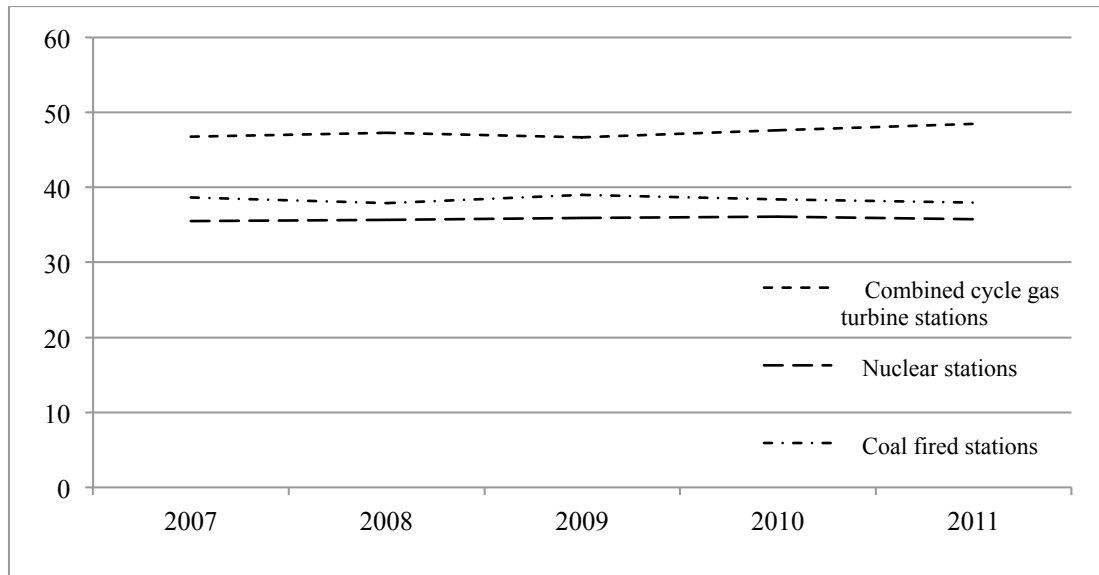
The following section sets out how this study will assess the points raised in this section and attempt to provide further detail on how intermittent sources of electricity will interact with the current electricity supply network.

## **7.2 Methodology**

### ***7.2.1 Assessing changes to plant efficiency***

The following method has been applied to UK power generation data in order to assess whether a change in efficiency of the conventional plant on the system can be associated with wind power capacity changes. Due to the issues raised in publications such as those above, further insight is needed into likely effects of an increase in the installed capacity of wind. The Digest of UK Energy Statistics' (DUKES) published each year by the Department of Energy & Climate Change (DECC) offers yearly information on the thermal efficiency of UK plant. In this case, thermal efficiency measures the efficiency with which the heat energy in fuel is converted into electrical energy. It is calculated for fossil fuel burning stations by expressing electricity generated as a percentage of the total energy content of the fuel consumed (based on average gross calorific values). For

nuclear stations it is calculated using the quantity of heat released as a result of fission of the nuclear fuel inside the reactor.



**Figure 7.1:** Yearly average thermal efficiencies for CCGT, coal and nuclear plant in the UK (DECC 2012b)

Figure 7.1 shows average efficiencies for CCGT, nuclear and coal power plants over the period of time (2007 – 2011) where wind power has been increasing in the UK network. It indicated no major change to thermal efficiencies over this time. In order to further assess whether efficiency changes can be seen, as mentioned by the literature already discussed, the following analysis has been carried out.

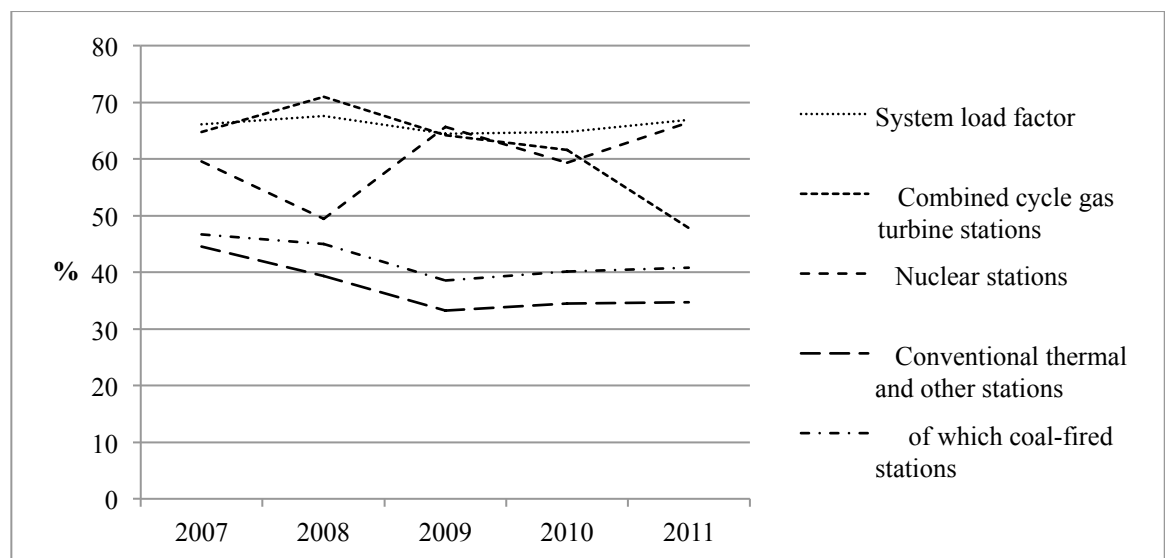
In order to assess the thermal efficiency of the thermal plant currently on the UK grid, thermal efficiency has been defined as total monthly fuel use in generation as a percentage of total monthly generation from plant using that fuel. This method means that actual plant efficiencies are captured from fuel use data, based on confidence in the data supplied by DECC. Monthly fuel use data can be found in the published DECC data, Table 5.4 and monthly electricity output in Table 5.4 (DECC 2012b).

Following calculation of thermal efficiencies of the plant, wind generation’s contribution to total system generation is calculated as a percentage. This procedure is carried out for data from July 2009 to June 2012, a period of 36 months and one that corresponds to a period of time where wind capacity has been steadily increasing in the UK by around 0.5GW per year (DECC 2012b).

This process is conducted for the fossil fuels, natural gas and coal in order to assess whether any change in efficiency can be associated with increasing wind capacity for both technologies. While it is often stated that gas plant and in particular, CCGT plant are the technology that is used to compensate for intermittent wind power (Qadrdan et al. 2010), it is also important to analyse whether coal plant are also reacting, especially since coal has recently become more expensive, after being much less expensive relative to gas as a fuel and this led the UK market to use coal for up to 40% of generation when it was relatively less expensive, more so than any other time since 1996 (Harrabin 2013). The depression in coal price had the effect of moving it up the merit order making gas more likely to be used for load balancing and network services, however this situation has recently reversed and has resulted in gas plants maintaining a share of electricity production in the second quarter (Q2) of 2015 equal to that in Q2 of 2014 while coal's share has decreased by nearly 8% (DECC 2015).

### 7.2.2 Assessing changes to load factor

Looking solely at plant efficiencies may not tell the full story since the following graph suggested that there is indeed a decrease in the average yearly load factors of CCGT and coal plant.



**Figure 7.2:** Yearly average plant load factors (%) for CCGT, coal, nuclear plant and the whole system in the UK (DECC, 2012; Table 5.10)

Since the system is not seeing a significant decrease in load factor, something must be causing the thermal plants' load factors to be decreasing over the years from 2007 to 2011 as seen above. The global recession of 2007/8 that was also felt in the UK also



will have contributed to a decrease in demand, although this is not certain. In order to better understand the changes to load factor, the following analysis has been carried out. This methodology is taken from Peacock's (2010) thesis in Chapter 8, "Attributing CO<sub>2</sub> emissions to load following protocol" and applied to total electricity generation data by fuel type (obtained from [www.elexonportal.co.uk](http://www.elexonportal.co.uk)) for the years, 2013 and 2014. December 2013 saw a particularly high electricity contribution from wind power; an average of 10.8% wind contribution over the month, with a peak contribution of 16.8% on 21<sup>st</sup> December 2013.

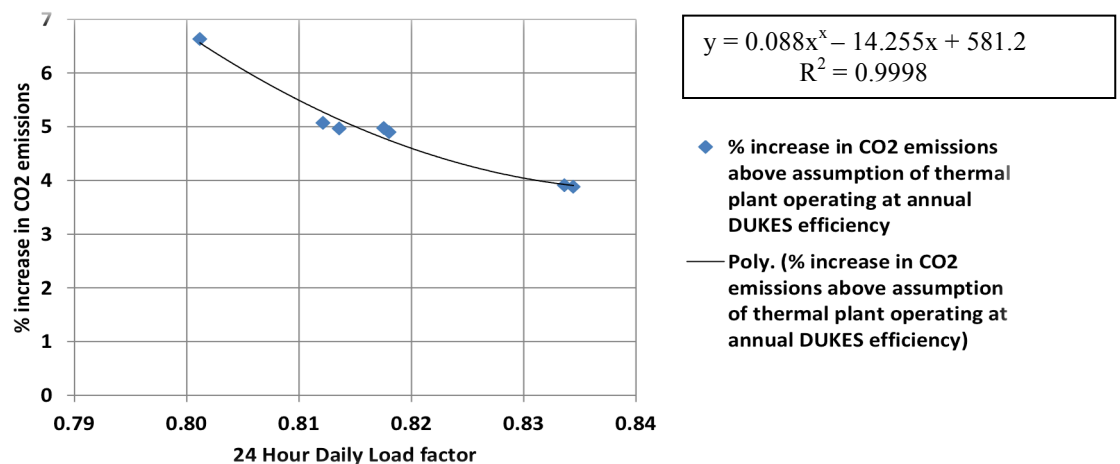
The approach is based on the assumption that increased supply variability (as expressed by a 24 hour load factor) will reduce the efficiency of operation of thermal plants. These numbers are based on averages, which do not resolve the effects of variation due to short-term intermittency.

No estimate is therefore included for issues that may result from prediction errors. As mentioned already, these errors would further worsen the situation so this estimate should be seen as conservative. A procedure is thus established which is outlined below. As with the assessment of plant efficiency changes, it is important to mention that this analysis uses historical UK data to determine the relationship between wind variability's affect on overall supply variability and associated CO<sub>2</sub> emissions. The same approach could be applied to more recent data assuming the relevant data could be obtained and manipulated in a similar manner.

Procedure Steps (points 1-3 from Peacock (2010)):

1. The load status of all generating units is defined.
  - a. An 'average' efficiency benchmark carbon intensity for electricity generation has been defined. This was conducted (Peacock 2010) for a winter week in 2005 for each individual plant (BM Unit Report data) for England and Wales and defined the load status and operating conditions in relation to efficiency change effects on fuel use of all of these contributing generating units.
  - b. Carbon intensity factors were assigned for each generating unit based on average efficiencies of plant and emissions figures for the respective generation types and electricity through UK interconnectors using the DUKES data for 2012 (DECC 2013), except for wind which has an

- average emissions factor defined as 17.1gCO<sub>2</sub>/kWh from Chapter 5’s review of historic wind farm GHG assessments, and electricity coming from other countries from the Government GHG conversion factors for company reporting (Defra/DECC 2013a). From these first two steps, the total CO<sub>2</sub> emissions that are attributable to real generation were obtained.
2. The operating efficiency carbon intensity for electricity generation was used which was defined by Peacock (2010).
    - a. This was done by first defining efficiency curves for thermal plants, versus their output. Efficiency curves have been defined (Peacock 2010; Figure 8-8) and all thermal plants are considered to act in a similar way in relation to varying capacity factor.
    - b. The warming status for thermal plants was defined, dependent on their ramp rate capability and time since last operation (Peacock 2010; Tables 8-3, 8-4).
    - c. The total emissions attributable to generation using efficiency curves and warming assumptions were then re-calculated.
  3. A relationship between load variability and emissions attributable to generation was established. For each day of the week, the load factor of demand has been determined. From this, CO<sub>2</sub> emission increase (or decrease) was defined for each day, associated with operational rather than average efficiency.
    - a. A relationship between load variability and CO<sub>2</sub> emissions was created from this procedure. This was done for a winter week in 2005 (see Figure 7.3, (Peacock, 2010; Figure A4-2)).



**Figure 7.3:** Relationship between load variability and percentage increase in CO<sub>2</sub> emissions based on BM Unit Report data for the period 20<sup>th</sup> to 26<sup>th</sup> January 2005 (Peacock 2010)

The following procedure steps utilise the relationship found in procedure steps 1-3:

4. The relationship in Figure 7.3 is applied to historical data for 2013 and 2014 (24 months), accounting for increased load variability caused by relatively high variable wind power generation.
  - a. The daily load factor of demand is defined for each day in the period, from electricity generation by fuel type in 30-minute intervals. The load factor of the residual demand is then calculated by subtracting the contribution from wind power.
  - b. The average change in load factor caused by the wind generation disaggregated by wind generation contribution as a percentage of demand. This establishes the contribution of wind generation to demand over this 24-month period.
  - c. Finally, using the relationship established in step 4 above, the additional CO<sub>2</sub> emissions attributable to thermal plants caused by wind generation variability for the defined period are obtained.
5. Define gross and net CO<sub>2</sub> emission savings from wind generation.
  - a. This is done firstly assuming coal plant are turned down and then secondly for CCGT plant being turned down, as with previous assessment of efficiency changes.
  - b. Finally, the net CO<sub>2</sub> savings are defined by subtracting the additional CO<sub>2</sub> emissions attributable to wind as a consequence of load variability from the efficiency benchmark defined in step 1.

It should be noted that the UK electricity supply network will not ‘choose’ either coal or gas to reduce power generation but this analysis allows for comparison between the technologies in relation to their GHG emissions.

The analysis explained in Section 7.2.2 is based on the assumption that increased installed wind capacity will increase variability of thermal plant generation. This should manifest itself as a decreased efficiency in thermal generation.

## 7.3 Results

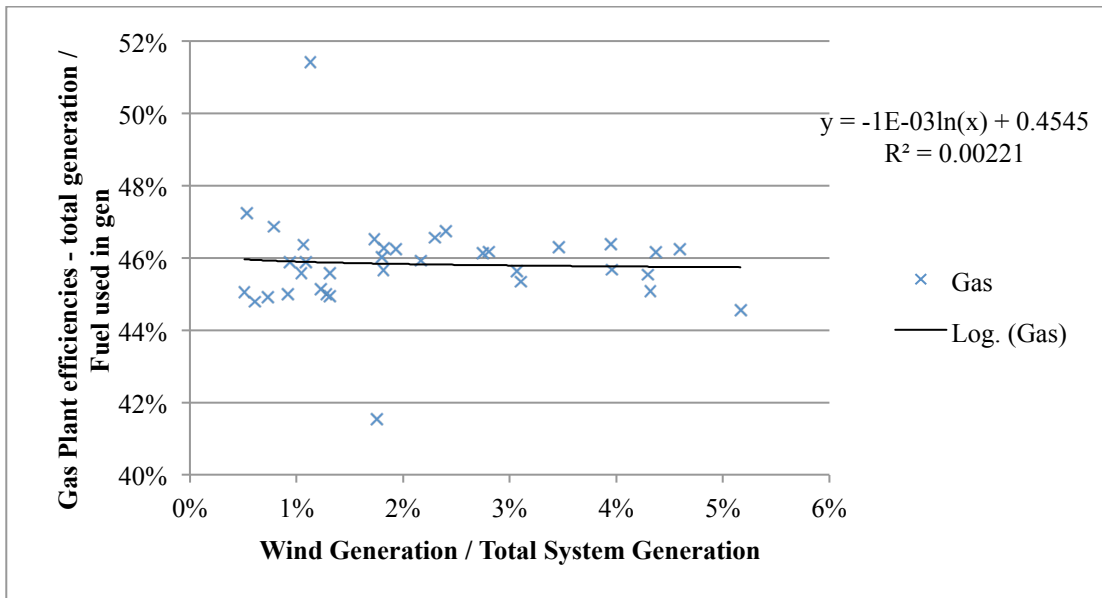
### 7.3.1 *Plant efficiency*

Table 7.1 shows the calculated efficiencies for both coal and gas power generation for the period outlined in Section 7.2 on a monthly basis. Also shown is the relative contribution of wind power to the total energy supplied for each month.

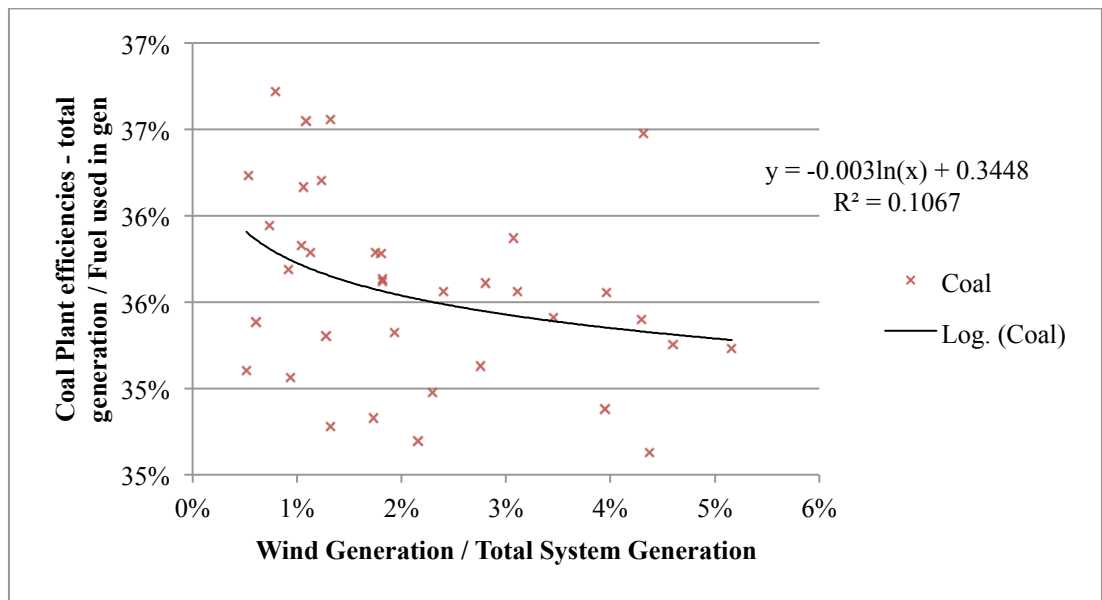
The results in Table 7.1 were plotted for gas (Figure 7.4) and coal (Figure 7.5) respectively against wind power's contribution to total system generation in order to assess whether a relationship could be found between wind contribution and plant efficiency, defined as total generation from the plant fleet over fuel used in generation at those plant.

<i>Year</i>	<i>Month</i>	<i>Efficiency of Coal - Total gen / Coal used in gen</i>	<i>Efficiency of Gas - Total gen / Gas used in gen</i>	<i>Wind Gen /Total Gen</i>
2009	July	36%	45%	0.7%
	August	35%	45%	1.3%
	September	36%	45%	1.2%
	October	36%	46%	1.0%
	November	37%	45%	1.3%
	December	37%	47%	0.8%
2010	January	37%	46%	1.1%
	February	36%	47%	0.5%
	March	36%	46%	1.1%
	April	36%	45%	0.9%
	May	35%	45%	0.5%
	June	35%	45%	0.6%
	July	35%	46%	1.3%
	August	35%	46%	0.9%
	September	36%	46%	1.8%
	October	35%	46%	1.9%
	November	36%	42%	1.8%
	December	36%	51%	1.1%
2011	January	36%	46%	1.8%
	February	36%	47%	2.4%
	March	36%	46%	1.8%
	April	35%	46%	2.8%
	May	35%	46%	4.4%
	June	35%	46%	2.2%
	July	35%	47%	1.7%
	August	35%	47%	2.3%
	September	35%	46%	3.9%
	October	35%	46%	4.6%
	November	35%	46%	4.3%
	December	35%	45%	5.2%
2012	January	36%	45%	4.3%
	February	36%	46%	4.0%
	March	36%	45%	3.1%
	April	36%	46%	3.1%
	May	36%	46%	2.8%
	June	35%	46%	3.5%

**Table 7.1:** Total gas and coal efficiency (total generation / fuel use) and wind contribution (wind generation / total system generation) from July 2009 to June 2012



**Figure 7.4:** Gas plant efficiencies in relation to wind power contribution as % of total supply



**Figure 7.5:** Coal plant efficiencies in relation to wind power contribution as % of total supply

In both gas and coal generation, there might be a reduction in plant efficiency that could be attributable to wind power's increasing contribution to total system generation. In particular, coal efficiency reduces by a larger amount. However, it can be seen from the calculation of the coefficient of variation ( $R^2$ ) that there is not a strong level of correlation between plant efficiency and wind contribution in either set of results. A logarithmic best-fit line was chosen since it provides the most positive coefficient of variation. The Figures 7.4 and 7.5 may suggest that efficiency decreases seen over the

studied period cannot be assigned to wind power alone. There will also be seasonal and diurnal variation.

Figure 7.1 (p185) has suggested that there is no change in efficiency over the period except a small increase in gas use. This would support the response by National Grid that it is difficult to link the variations of efficiency of gas fired power stations directly to wind intermittency (National Grid 2012a). It has also been assumed that increased penetration of wind will automatically increase intermittency but as discussed in Chapter 3, increased wind penetration may be accommodated by increased geographical diversity in wind location which could smooth wind forecasting errors and output since the total wind output would be less sensitive to local effects (Sinden 2007a). The correlation may therefore not be as strong as suggested.

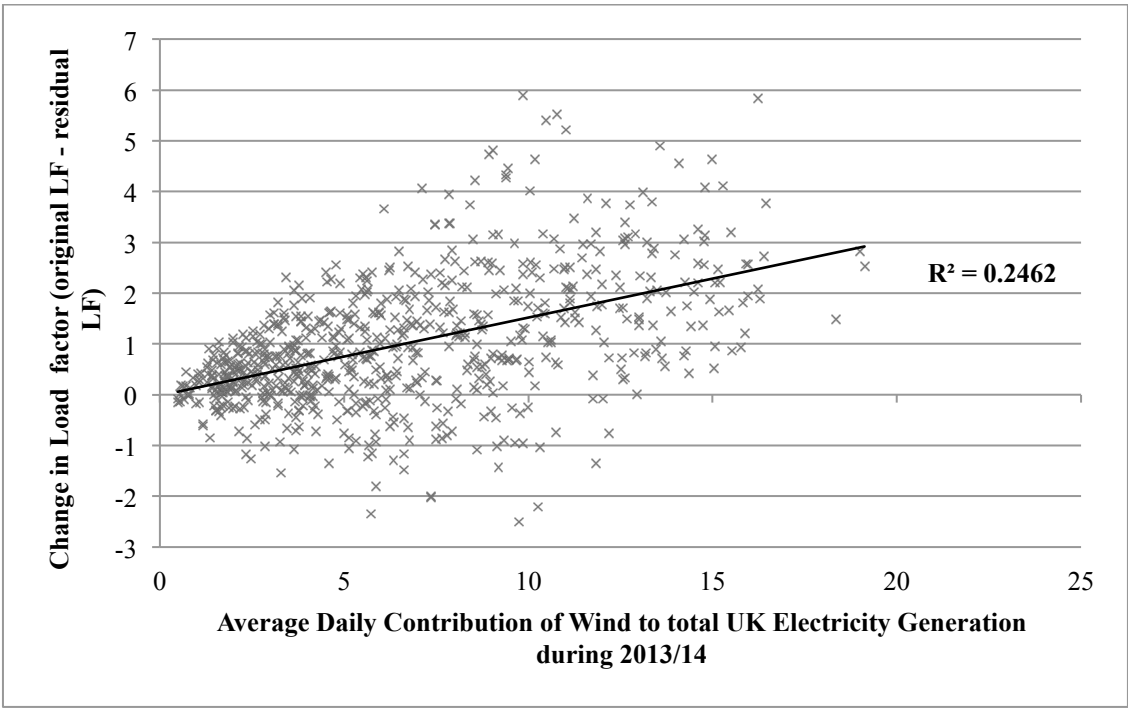
### **7.3.2 Load Factor**

Following procedure steps in Section 7.2.2, the relationship in Figure 7.3 was established between load variability and emissions attributable to generation. While there are only a few data points, there is a high degree of correlation, as represented by calculation of the coefficient of variation ( $R^2$ ), between daily load factor changes and percentage increase in CO<sub>2</sub> emissions. So, at 81% load factor for example, it is shown that CO<sub>2</sub> emissions are 5.5% higher from UK thermal plants than would have occurred when operating at annual efficiencies defined by DECC (2013).

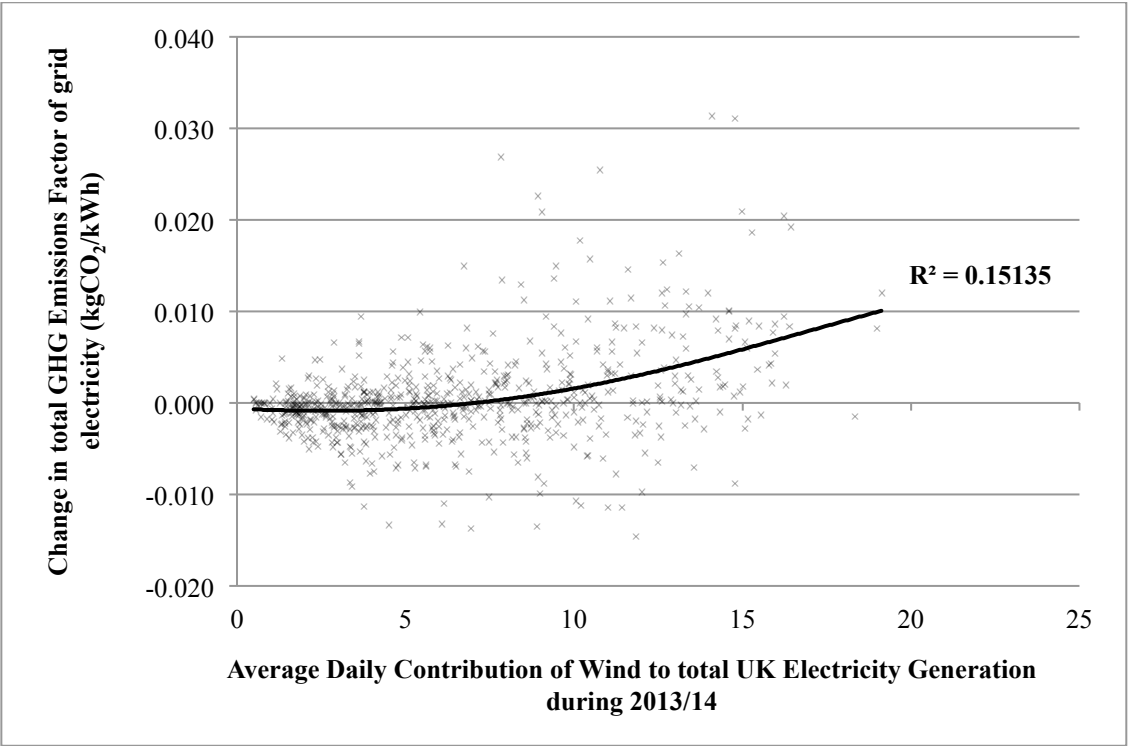
Following procedure step 4 in Section 7.2.2, the relationship established has been applied to 2013 and 2014 UK generation data, accounting for assumed increased load variability caused by wind generation. This is shown in Figure 7.6.

The resulting change in UK grid electricity GHG emissions factor with respect to an increase in daily average wind power contributions to electricity supply is shown in Figure 7.7 for the 24-month period of 2013-14.

Figure 7.7 has calculated the relative change in the GHG emissions factor for total grid electricity in the UK as a result of the change in load factor shown above in Figure 7.6.



**Figure 7.6:** Change in load factor with respect to wind power contribution to total electricity generation during 2013/14



**Figure 7.7:** Change in UK grid electricity GHG emissions factor with respect to wind power's contribution to total electricity generation during 2013/14



As a result of the above relationship in Figures 7.6 and 7.7, the following net GHG emissions savings from wind relating to both coal plant turndown and CCGT plant turndown during 2013-14 can be estimated and are shown in Table 7.2.

The ‘factor’ column in Table 7.2 is calculated using the relationship established in Figure 7.3 for determining the percentage change in GHG emissions when daily load factor of the electricity supply system changes.

$$y = 0.088x^2 - 14.255x + 581.2 \quad (7)$$

Where:

y – percentage increase in GHG emissions

x – 24 hour daily load factor

The ‘factor’ in Table 7.2 equals the average daily percentage increase of GHG emissions for each load factor. The load factors are determined by:

1. Maximum efficiency relates to system running as if all power plants ran at maximum efficiency and were not ramped down to match demand.
2. Original load factor is found by using the relationship (Equation 7) in Figure 7.3 to establish a change in GHG emissions for load following by all generation technologies.
3. Residual load factor is found by using the relationship (Equation 7) in Figure 7.3 to establish a change in GHG emissions for load following by all generation technologies except for wind power.

<i>Accounting for Load Factor</i>	<i>Factor</i>	<i>Total Emissions</i>	
Total Emissions – maximum efficiency		46,749,821,746	kgCO <sub>2</sub>
Total Emissions - original Load Factor (a)	5.4%	49,274,779,618	kgCO <sub>2</sub>
Total Emissions - residual Load Factor (b) (wind power 6-7% of demand)	5.5%	49,329,009,412	kgCO <sub>2</sub>
Emissions attributable to wind variability (c)	(a) – (b)	54,229,793	kgCO <sub>2</sub>
Total Generation		103,192,772,167	kWh
Total Wind Generation (d)		6,627,272,167	kWh
<i>Additional kWh attributable to grid emission factor due to variability of wind</i>	(c) / (d)	<b>0.008</b>	<b>kgCO<sub>2</sub>/kWh</b>

**Table 7.2:** Effects of Load Variability on Total Emissions from Electricity Generation during 2013/14

Table 7.3 assumes coal plant turndown and then gas plant downtown and calculates total avoided emissions as a result of wind power contributing the equivalent generation, seen in Table 7.2 ('total wind generation'). Total emissions are calculated by multiplying GHG emissions factors by 'total wind generation'. Net savings are calculated by subtracting 'emissions attributable to wind variability' in Table 7.2 from total gross emissions in Table 7.3.

	<i>GHG Emissions Factors kgCO<sub>2</sub>/kWh</i>	<i>Total Emissions (kg)</i>	<i>% of total emissions</i>
Gross emissions offset from wind - assume coal plant turndown	0.895	5,931,408,589	12.7%
Gross emissions offset from wind - assume CCGT plant turndown	0.415	2,750,317,949	5.9%
<b>Net emissions</b> saving from wind - assume coal plant turndown		5,877,178,796	12.6%
<b>Net emissions</b> saving from wind - assume CCGT plant turndown		2,696,088,156	5.8%

**Table 7.3:** Gross and Net GHG emissions saving from wind power for coal or gas power plant turndown

The average change to the total GHG emissions factor over the 24-month period is estimated to be 8gCO<sub>2</sub>/kWh (with the average wind power contribution of 6.42% over the period of 2013 and 2014). Taking individual daily readings, a large change in the GHG emissions factor is estimated to be 26gCO<sub>2</sub>/kWh on 21<sup>st</sup> December 2013, occurring when the wind contribution equals 16.8%. This may suggest that even though this contribution is the maximum wind contribution during this period, it occurs at a time of day least suited to matching electricity demand since thermal plants have to react and cause the largest change in GHG emissions factor. This may also suggest that as wind power contributes more to total UK electricity, its ability to reduce total GHG emissions of grid electricity will decrease, when used in the current electricity supply network system. It is important to ensure that the changes in GHG emissions factors are not compared directly to total life cycle GHG estimates for wind power since this is part of the total system. On the other hand, during periods when wind power output matches periods of demand, a reverse effect occurs where the emissions factor change is negative i.e. the wind farms are reducing overall emissions by both supplying 'low-carbon' electricity and causing thermal plants to operate efficiently.

Based on this research, it is not the case that the load variability of wind power is in effect offsetting the total net benefit of wind power in reducing overall GHG emissions. This is seen in Table 7.2, which shows that wind power still provides a net reduction to total GHG emissions from electricity in relation to both coal plant turndown and CCGT downturn. This relates to a net GHG emissions saving as a result of wind power of 12.6% and 5.8% for coal and gas plant turndowns respectively, which are 0.1% less than previously estimated without taking into account the load variability of wind power. This is perhaps a crucial piece of evidence that has previously been disputed to date. These estimations are in contrast to Hughes (2012a) who does not consider the system as a whole and compares the relative merits of individual plants whilst also not considering how electricity generation meets demand. These could be seen as reasons for the difference in estimates of the effects of load variability of wind power on the UK electricity supply network in relation to changes in total associated GHG emissions factors for UK electricity.

The results show that in general, the associated effects of wind power on overall emissions per kWh of electricity equate to an average increase of  $8\text{gCO}_2/\text{kWh}$  to a previously un-accounted for effect, based on this chapter's calculations from considering generation data for 2013 and 2014. This can be compared with figures for total life cycle emissions from wind power of  $16\text{gCO}_2/\text{kWh}$  for onshore projects and  $18.2\text{gCO}_2/\text{kWh}$  for offshore projects, based on the harmonisation of historic life cycle estimates from wind power in Chapter 5. It can be argued that this figure should in effect be included in quoted figures for life cycle GHG emissions estimates for wind power. In other words these effects could be said to equate to approx. 50% of total life cycle GHG emissions associated with wind power and so could be seen as significant in terms of reducing the efficacy of wind power in reducing GHG emissions associated with electricity generation. However, when comparing with current emissions factors per kWh for UK electricity of  $0.497\text{kgCO}_2\text{e}/\text{kWh}$  from DECC's GHG conversion factors, this figure represents less than 0.2% of total emissions at present. This may suggest that the perceived problem discussed is affecting the UK networks but not as significantly as some (Hughes 2012a) may suggest. This would also suggest that National Grid's preliminary estimates and response to the Scottish Government are in fact also closer to the truth than other commentators. More research needs to be

conducted in order to further understand the change in the total GHG intensity factor for UK electricity as wind power's contribution to total generation continues to increase.

#### **7.4 Conclusions**

The effects of intermittent wind power on current electricity supply networks need to be better understood. There is a definite effect of load variability of wind generation on thermal plants in the UK system that reduces the net emissions saving from wind power. Based on this assessment of wind power's effects on UK thermal plants, this effect could be considered insignificant (0.15%) when compared to the UK electricity's carbon-equivalent intensity. It is also large in comparison to total GHG life cycle emissions from the manufacture, construction, running and decommissioning of wind farms, equating to 5% of the total average of associated GHG life cycle emissions. However, the range of change to the overall GHG emissions factor also suggests that further research needs to be conducted to fully understand this relationship. There are also numerous other factors influencing thermal plant efficiencies that should be better understood. Weather forecasting in particular will play more of a role in affecting fossil fuel use into the future due to more efficient use of thermal plants in conjunction with wind power output. Further work is needed to understand whether there is an optimal installed capacity of wind to avoid detrimental effects on carbon reduction of electricity. This should also be seen as a conservative estimate again here. The small effect found is based only on 24 hour load factors and ignores other factors such as forecast errors which are estimated by some to lead to cost implications in the range of 4.3 and 6.7€ per MWh of wind energy for wind power penetrations between 5% and 30% of the annual energy demand (Bruninx et al. 2013).

## **Chapter 8 – Conclusions**

Wind power's contribution to global electricity production is set to continue to grow rapidly for the foreseeable future. The growth of any technology requires considered planning, based on its intended purpose. In this case, renewable electricity production technologies are being commissioned in order to reduce the GHG emissions associated with large-scale regional electricity production and reduce a region's dependence upon depleting fossil fuels, while ensuring security of supply of electricity. This thesis has outlined these purposes, reviewed the technological requirements for adding wind power to an electricity supply network such as that in the UK, assessed historic GHG assessments of wind farm projects and conducted a novel GHG assessment of Ormonde Offshore Wind Farm, one of the largest offshore wind farms to date to be studied in this manner. Finally, an estimate for the reduction of net GHG emissions saving has been calculated to show the effect of load variability of wind power on thermal plant in the same supply network.

This chapter firstly summarises the core reasons that have encouraged investment in technologies that will generate low carbon electricity and the state of assessing their potential to reduce overall associated GHG emissions. Secondly, this chapter will summarise the findings of this thesis in relation to variations in the estimations of associated GHG emissions from wind power and other knock-on effects of adding intermittent electricity sources into a traditional electricity supply network such as the situation found in the UK. Finally, suggestions for further work are presented that might further illuminate the critical factors that affect the assessment of low carbon electricity infrastructure in relation to their ability to reduce associated GHG emissions.

### **8.1 Introduction**

This thesis has assessed the state of the UK Energy sector in relation to reducing associated GHG emissions through deployment of renewable technologies such as wind turbines. It has then reviewed the current state of Life Cycle Assessment (ISO LCA) and in particular, associated GHG estimation in order to learn valuable lessons and highlight the inherent difficulties with modelling systems to estimate environmental impacts, such as Global Warming Potential (GWP). Following this, historic estimates of associated GHG emissions have been harmonised in order to reduce uncertainty in these

estimates and better understand the critical factors that affect such estimation. This has shown how estimating associated GHG emissions of wind farms can result in large variation as a result of both the methodological choices made and the assumptions chosen. This thesis has sought to reduce some of the doubt over these choices and then offer a novel hybrid approach to GHG assessment through using publicly available information on project costs and embodied GHG data. This procedure has produced an estimation of associated GHG emissions for Ormonde Offshore Wind Farm that is within the range of those harmonised historic estimates of associated GHG emissions from wind farms and suggests that while this method does not guarantee a fully accurate estimation, it reduces time and data constraints of conducting an estimation and also relates to more tangible project information in the form of costs. This methodology also ensures that no data gaps are present in the estimation of associated GHG emissions for a wind farm. The following sections summarise conclusions from each stage of this thesis.

## **8.2 The Reasoning for GHG Estimation**

The nature of the debates within the climate science arena has left those who decide on policy and academics with a confused picture and one that has increased resistance to definitive action. Clearly, this is not in the best interests of decision-makers. A reduction in fossil fuel requirements throughout the global economy could only lead to a long-term reduction in dependence on an insecure supply. The threats of peak fossil fuel production gives the opportunity to better discuss UK energy goals and allow all parties to reach a common ground. The current EU legislation that has shaped UK legislation is focussed on emissions. Based on the evidence presented in Chapter 1, it is unwise to only consider these emissions without also including the consumption of carbon-rich products. The best course of action for the UK is one of whole life cycle thinking of available technologies in order to understand and reduce the resource costs of energy projects. Electricity, and associated GHG emissions, feeds into every aspect of the UK economy.

As a result of the literature review in Chapter 2, it is recommended that the UK government should:

1. Reduce the emphasis on climate change projections and threats that still contain a degree of uncertainty that is not measurable.

2. Utilise technologies that are not only focussed on producing low associated GHG emissions but are not unreasonably expensive during their whole life cycles.
3. Discuss peak oil and the associated risks in greater depth.
4. Move to a standard GHG emissions accounting practise that monitors consumption-based carbon emissions immediately.

### **8.3 Challenges and Opportunities for the UK Energy Sector**

In terms of the type of generation technologies that will predominantly make up our energy mix, life cycle assessment will become increasingly important to track indirect emissions due to the characteristics of low carbon technologies having relatively low environmental impacts in the use phase of their life cycles. Renewables, namely wind power in this instance, can provide the target 2020 generation contributions. A key aspect will be intermittency planning and back-up capacities. Again, life cycle assessment should be in place to correctly track energy use and emissions.

Energy security, assessed by de-rated generating capacity should be the key driver in order to ensure sufficient supply. Without a secure energy future, there will be less economic ability to afford to reduce GHG emissions.

Given that as wind's contribution increases, its relative capacity credit decreases, it should be recognised that a diverse electricity mix is of crucial importance. This will lead to greater efficiency in supply as well as a greater security of supply. It does not seem feasible or cost effective to attempt to meet all electricity targets with only wind or a similarly intermittent technology. It could also be argued, based on Chapter 7's assessment of the effects of wind power's intermittency on total emissions factor changes for UK electricity that large contributions of wind power to the system may result in adverse effects in relation to reducing overall GHG emission intensity. Chapter 3 presented both the challenges and opportunities relating to the UK's requirement for a large new contribution to installed capacity due to the retirement of much of the current capacity, especially of old coal-fired thermal plants. It is important that this situation is seen as the best way to improve the security of supply of electricity in relation to imports and to reduce the overall emissions from different technologies.

#### **8.4 The Use of GHG Estimation in Decision Making**

The following specific research questions were addressed in Chapter 4:

1. Can common problems in life cycle assessment be outlined in order to remove them in relation to a specific sector and its activities?
2. Can historic LCAs be critiqued in relation to a defined set of key characteristics (resulting from a highlighting of the problems in LCA) of the Life Cycle Assessment framework?
3. Can an improved standard framework be outlined for electricity supply technologies currently in operation or scheduled to contribute to UK electricity generation in the near future?

It has been shown that the development of LCA has led to acknowledgement of a number of common problems within the framework that can be discussed and reduced in relation to specific scales and technologies within a sector. The goal of using this set of common problems to critique historic LCAs and life cycle GHG assessments seems reasonable, especially since fewest problems tend to lie at the micro scale. Where larger problems still exist is in larger, macro studies and hence a bottom-up approach to assessment should be the optimum solution, before making decisions on large, macro studies.

#### **8.5 Assessment of Historic Life cycle GHG Assessment Methodologies**

Historic life cycle GHG estimates should be assessed by reviewing a number of important characteristics of the assessment: the system boundaries used; clearly presented assumptions and data sources; and the specific purpose of the GHG assessment. Based on this thesis, the assessment should use a hybrid approach of process analysis and cost-based analysis where possible. This also applies to the choice of data where gaps exist in process-based data. Economic data should only be used in place of gaps in data availability. Life cycle GHG emissions should be clearly presented so as to be able to compare with other life cycle assessments. Analyses of sensitivities and scenario choices should also be conducted where appropriate in order to better understand uncertainties in assessment and choices made during the assessment. Finally, the use of an internationally available inventory (or combination of such inventories) is also considered fundamental to future assessments.



The lessons learned from Chapter 4 were important for developing an effective methodology for estimating total life cycle GHG emissions through use of a hybrid approach. This hybrid methodology presented in Chapter 6 has been developed from the two standard attributional approaches of process-based and cost-based analysis, as discussed in Chapter 4.

## **8.6 Variation in historic wind farm associated GHG estimates**

Life cycle GHG emissions of wind power systems assessed in Chapter 5 ranged from 2 to 81gCO<sub>2</sub>e/kWh. While this could be considered a small absolute range for a power generation technology, it represents a difference of almost two orders of magnitude from the smallest to the largest value.

The range of life cycle GHG emissions was made much smaller through applying a harmonisation process for capacity factor and lifetime, and recycling processes (2.9 to 37.3gCO<sub>2</sub>e/kWh). The inter quartile range (IQR) for estimates reduced by 17% following harmonisation, which is much lower than the decrease in range, suggesting that average estimates in the IQR were relatively reliable. This is an important result for decision making since it helps to better understand the ranges of estimates and also better inform future GHG assessments. It also helps to dispel some myths in relation to wind power not being capable of reducing overall GHG emissions equivalent to those associated with the wind power life cycle.

There was relatively close agreement between onshore and offshore wind power systems in relation to their life cycle GHG emissions. This suggests that emissions from onshore and offshore installations are not substantially different. However, with offshore installations currently being the fastest area of development in wind power, particularly in Northern Europe, more studies will be required to further support or refute this claim. In particular, the additional life cycle stages involved with offshore installations such as the civil works required for grid connection and power transmission via direct current, if further than 50km from shore, should be focussed on to align GHG estimation with development in the wind industry.

There is too great a number of process-based LCAs in relation to wind power systems which are in conflict with LCA practitioners' suggestions (Crawford 2009) and could result in large truncation errors. Further studies should be conducted by hybrid

economic LCA as well as consequential LCAs in order to better understand the interaction of wind power with the rest of the power supply technologies currently available on electricity supply networks. In particular the effects of intermittency on thermal generation plants should be studied further.

### **8.7 A GHG assessment methodology for Wind Farms**

The true total life cycle GHG emissions that can be attributed to the Ormonde Offshore wind farm project will likely lie within the results given above. It is impossible to know exactly what this answer is but by highlighting the various issues in estimating this figure, it can be seen that some assumptions made by the assessor are more important than others. These will become ever more apparent as more life cycle studies are published but through a harmonisation study in Chapter 5 and this chapter's case study, it can be clearly seen that hybrid analyses, while offering the highest estimates, also include far more of the project's stages than either the process or cost-based analyses. While this is intuitive, it should also be seen that the perceived complexity of hybrid analyses could be reduced through further research into cost breakdowns of wind farms and the allocation of these costs across the lifetime of a wind farm. Decision-makers should be wary of any life cycle estimate that does not make it clear which critical factors (predominantly capacity factor and lifetime) are chosen and why, along with methodological choices for recycling and dataset choices. The clearer the life cycle study is on the critical factors it assumes, the easier it is for a decision-maker to see the possible range on which to base future decisions.

An important element of the life cycle study provided in this thesis is lacking. This is the likely effects of wind farms on an electricity supply network such as that in the UK where traditional plant are also contributing to total generation and the dynamics of their interaction. This was discussed in Chapter 7 in order to attempt to assess whether intermittent power generation has a detrimental effect on the efficiencies of the traditional power plant fleet.

### **8.8 The interaction of intermittent power sources with the electricity supply network**

The effects of intermittent wind power on current electricity supply networks need to be better understood. There is a definite effect by the load variability of wind on thermal plant in the same system that reduces the net emissions saving from wind power. Based

on load factor assessment of wind power's effects on UK thermal plants, this effect is considered to be small (<1%) when compared to the UK electricity's carbon-equivalent intensity of 0.497kgCO<sub>2</sub>e/kWh. It is large in comparison to total GHG life cycle emissions from the manufacture, construction, operating and decommissioning of wind farms, equating to 50% of the total average. This relates to a net GHG emissions saving as a result of wind power of 12.6% and 5.8% for coal and gas plant turndowns respectively, which are 0.1% less than previously estimated without taking into account the load variability of wind power. However, the range of changes to the overall GHG emissions factor also suggests that further research needs to be conducted to fully understand this relationship. There are also numerous other factors influencing thermal plant efficiencies that should be better understood. Weather forecasting in particular will play more of a role in affecting fossil fuel use into the future due to its ability to better match wind power output with scheduling of the UK thermal plant fleet. Further work is needed to understand whether there is an optimal installed capacity of wind to avoid detrimental effects on carbon reduction of electricity.

## **8.9 Further Work**

The following points would help to further improve the state of estimating associated GHG emissions with energy projects.

1. Further definition of key terms should be made through standardisation of a specific technology and to be followed by the sector. This refers to Chapter 4 (Figure 4.1 and Table 4.1) where functional unit, boundaries and standard scenarios can be defined for a basic, standardised LCA of wind power.
2. Key criteria that are not directly included as a result of the above point should be reviewed such as cut-off criteria for specific technologies, referring to where assessment ceases to consider possible associated emissions out with boundaries. Local technical uniqueness also requires further research and this is assessed in Chapter 6 whereby historic LCAs are reviewed in order to attempt to remove local uniqueness impacts. Allocation such as possible interactions with other technologies requires further research. This was considered in Chapter 7 where wind power interacts with thermal power plants on an electricity supply network in the UK.
3. Data availability and quality requires continuous review as occurs with the Ecoinvent, and other established, database. A method should be further

developed for each technology in order to highlight each assessment's data quality.

4. Databases that are most appropriate for a given sector must be outlined and any gaps should be filled as quickly as possible or a reasonable range suggested through use of economic data in the form of hybrid assessment. Hybrid assessment has been used in Chapter 6 and further research into each technology's costs in relation to use in hybrid LCA will improve the quality of this data provided accurate costs are known and are made available.
5. A review into specifying types of data for consequential LCAs and specific data for attributional LCAs of projects within the power sector should be conducted. This will require research at a micro level.
6. Further work should be carried out on current methods of presenting uncertainty in LCAs and life cycle GHG assessments of power infrastructure in order to better understand current practice and stakeholder awareness.
7. Life cycle GHG assessment should include some time aspect and further work should be done on how this may affect the mitigation potential of each technology.

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## **PUBLICATIONS**