Sustainability Assessment of Wind Turbine Design Variations: An Analysis of the Current Situation and Potential Technology Improvement Opportunities

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Sustainability Assessment of Wind Turbine Design Variations: An Analysis of the Current Situation and Potential Technology Improvement Opportunities

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Abstract

Over the last couple of decades, there has been increased interest in environmentally friendly technologies. One of the renewable energy sources that has experienced huge growth over the years is wind power with the introduction of new wind farms all over the world, and advances in wind power technology that have made this source more efficient. This recognition, together with an increased drive towards ensuring the sustainability of wind energy systems, has led many to forecast the drivers for future performance.

This study aims to identify the most sustainable wind turbine design option for future grid electricity within the context of sustainable development. As such, a methodology for sustainability assessment of different wind turbine design options has been developed taking into account environmental, data uncertainty propagation and economic aspects. The environmental impacts have been estimated using life cycle assessment, data uncertainty has been quantified using a hybrid DQI-statistical method, and the economic assessment considered payback times. The methodology has been applied to a 1.5 MW wind turbine for an assessment of the current situation and potential technology improvement opportunities.

The results of this research show that overall, the design option with the single-stage/permanent magnet generator is the most sustainable. More specifically, the baseline turbine performs best in terms of embodied carbon and embodied energy savings. On the other hand, the design option with the single-stage/permanent magnet generator performs best in terms of wind farm life cycle environmental impacts and payback time compared to the baseline turbine. With respect to the design options with increased tower height, it is estimated that both designs are the least preferred options given their payback times. Therefore, the choice of the most sustainable design option depends crucially on the importance placed on different sustainability indicators which should be acknowledged in decision making and policy.

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List of Abbreviations

ADP	Abiotic Depletion Potential
AEP	Annual Energy Production
ALCA	Attributional Life Cycle Assessment
AP	Acidification Potential
BCE	Blade Material Cost Escalator
BOM	Bill of Materials
BWEA	British Wind Energy Association
CAPEX	Capital Expenditure
CCL	Climate Change Levy
CCS	Carbon Capture Storage
CDF	Cumulative Distribution Function
CFRP	Carbon Fibre Reinforced Plastic
CLCA	Consequential Life Cycle Assessment
CML	Centre of Environmental Science of Leiden University
CO_2	Carbon dioxide
CV	Coefficient of Variation
DQI	Data Quality Indicator
EEC	Embodied Energy Coefficient
EF	Emission Factor
EP	Eutrophication Potential
ESA	European Space Agency
FAETP	Fresh water Aquatic Eco-toxicity Potential

GBP	Great British Pounds
GDP	Gross Domestic Product
GDPE	Labour Cost Escalator
GHG	Greenhouse Gas
GWP	Global Warming Potential
HAWT	Horizontal Axis Wind Turbine
HDS	Hybrid Data Quality Indicator and Statistical
HTP	Human Toxicity Potential
I/O	Input-Output Analysis
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFIAS	International Federation of Institutes for Advanced Studies
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Organisation for Standardisation
K-S	Kolmogorov-Smirnov
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Lifecycle Cost of Energy
LEC	Renewable Levy Exemption Certificate
MAETP	Marine Aquatic Eco-toxicity Potential
MCS	Monte Carlo Simulation

MRE	Mean Magnitude of Relative Error
NASA	National Aeronautics and Space Administration
NEA	Net Energy Analysis
NMVOC	Non-Methane Volatile Organic Compounds
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
ODP	Ozone Depletion Potential
OFGEM	Office of Gas and Electricity Markets
OPEX	Operational Expenditure
PDF	Probability Distribution Function
POP	Photochemical Ozone Creation Potential
PV	Solar Photovoltaic
SETAC	Society of Environmental Toxicology and Chemistry
TETP	Terrestrial Eco-toxicity Potential
TIO	Technology Improvement Opportunities
UNEP	United Nations Environment Programme
USD	US Dollars
VAWT	Vertical Axis Wind Turbine

Acknowledgements

Over the course of my PhD research several people have provided invaluable help for which I would like to express my appreciation. Firstly, I would like to thank my supervisors Drs. Wai Ming Cheung and Reaz Hasan for giving me the opportunity to undertake this research. Their continued guidance, assistance, encouragement and support in the last three years have led to the completion of this PhD research. I also wish to thank Professor Nicola Pearsall, Dr John Tan and Dr Roger Pennington for their time and support during the annual progression and review meetings, much appreciated.

I especially thank my family for their continuous encouragement, understanding, patience and support all through the duration of this work. Your belief in me is boundless and I hope I can continue making you proud.

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Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented in this thesis has been approved. Approval has been sought and granted by the Faculty Ethics Committee / University Ethics Committee / external committee (RE17- 01-131639) on (5th April, 2013).

I declare that the Word Count of this Thesis is 45,797 words

Name:

Signature:

Date:

Chapter 1 Introduction

1.1 Sustainable Development

In recent years, sustainable development has been incorporated into several levels of society. The Brundtland Commission's standard definition "*to make development sustainable - to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland et al., 1987) is a foundation for most who set out to describe the concept. Kates and Clark (1999) contends that sustainable development has three important components: what is to be sustained, what is to be developed, and the intergenerational component. Sustainable development is frequently presented as being divided into environment, economy and society (Brundtland et al., 1987; Kates and Clark, 1999; Ness et al., 2007) (Figure 1-1).

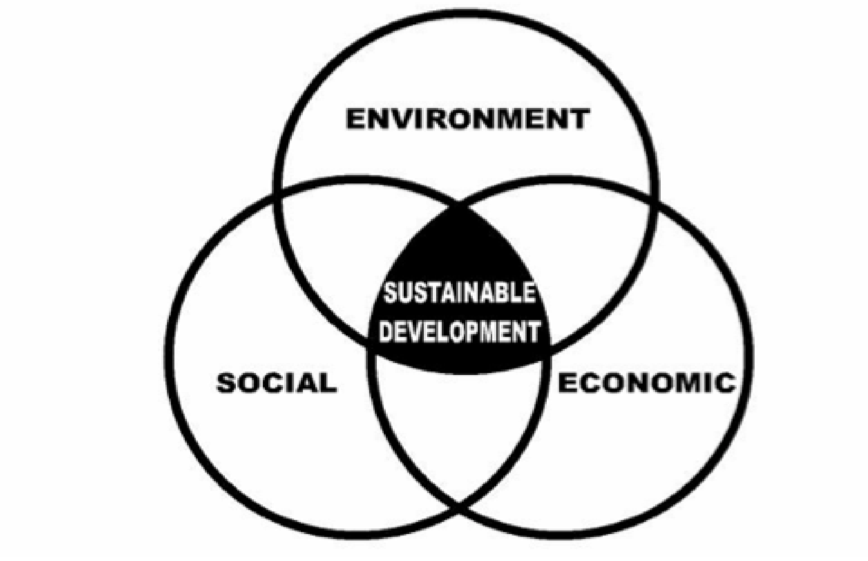


Figure 1-1. Venn diagram of sustainable development (Kates and Clark, 1999)

According to Ness et al. (2007), for the transition to sustainability goals must be assessed. This has presented significant challenges to the scientific community in providing methodical but reliable tools. In response to these challenges, sustainability assessment has become a rapidly evolving area. Sustainability assessment is defined in Devuyst et al. (2001) as "*a tool that can help policy-makers and decision-makers decide which actions they should or should not take in an attempt to make society more sustainable*". Sustainability indicators are increasingly acknowledged as a useful tool for public communication in conveying information on the performance of countries in fields such as economy, society, environment and technological development as well as policy making (Ness et al., 2007). There is a widely acknowledged need for societies, organisations and individuals to find tools, models and metrics for articulating the extent to which current activities are unsustainable. However before development of the indicators and methodology, what is required is the clear definition of the policy goals towards sustainability.

1.2 Energy Supply and the Environment

There is a persistent need to hasten the expansion of innovative energy technologies with the aim of addressing the global challenges of climate change, sustainable development and clean energy. To achieve the envisioned emission reductions, the International Energy Agency (IEA) has undertaken efforts to develop global technology roadmaps, in close consultation with industry and under international guidance (IEA, 2009). These technologies are evenly divided among supply-side and demand-side technologies and consist of several renewable energy technologies. The general aim is to promote global development and acceptance of important technologies to curb mean global temperature increase to 2°C in the long term (IEA, 2013). The roadmaps will allow industry, financial partners and governments to identify steps necessary and administer measures to encourage the necessary technology development and acceptance.

The roadmaps take a long-term outlook, but emphasize in particular the important actions that should be taken by individual stakeholders in the next decade to reach their goals. This is because the activities embarked on within the next five to ten years will be critical to achieving emission reductions in the long-term (IEA, 2013). Current conventional power plants along with those under construction lead to a guaranteed CO_2 emissions increase since they will be operating for years. According to IEA (2012), premature retirement of 850 GW of existing coal capacity would be necessary to reach the goal of curbing climate change to 2°C. It is therefore crucial to develop low-carbon energy supply in the present day.

1.3 Justification for Wind Power in the Overall Energy Context

IEA Energy Technology Perspectives 2012 (ETP 2012) forecasts that in the absence of new policies, energy sector CO_2 emissions will increase by 84% above 2009 levels by 2050 (IEA, 2012). The ETP 2012 model looks at competition between different technology solutions that can contribute to averting this increase: near-decarbonisation of fossil fuel-based power generation, renewable energy, nuclear power and greater energy efficiency. Instead of projecting the maximum possible deployment of any given solution, the ETP 2012 model carries out a calculation of the least-cost mix to realize the CO_2 emission reduction goal necessary to curb climate change to 2°C. ETP 2012 shows wind power providing 15% to 18% of the required CO_2 reductions in the electricity sector in 2050, up from the 12% projected in ETP 2008 (IEA, 2008). This increase in wind power offsets slower progress in the intervening years in the area of higher costs for nuclear power and carbon capture and storage (CCS). However, it also reveals faster cost reductions for some renewable technologies, including wind power.

Wind energy, like other renewable resources based power technologies, is widely available globally and can contribute to energy import dependence reduction. As it involves no fuel price risk, it improves security of supply. Wind power improves energy diversity and safeguards against fossil fuel price unpredictability thus, stabilising electricity generation costs in the long term (IEA, 2013). Wind power involves no direct greenhouse gas (GHG) emissions, does not emit other pollutants (e.g. oxides of nitrogen and sulphur) and consumes no water. As extensive fresh water use for cooling of thermal power plants and local air pollution are becoming significant concerns in dry or hot regions, the advantages of wind power become ever more important.

1.3.1 Wind - What Is It?

The content of this section is based on an article by the National Aeronautics and Space Administration (NASA, 2003).

Wind is air flowing across the surface of the earth. Winds are produced by differences in atmospheric pressure that force air to flow from areas of higher pressure to areas of lower pressure. On the surface of the earth, the differences in pressure are as a result of uneven heating of the surface by the sun. The ensuing wind patterns are largely the result of both the rotation of the earth and pressure gradient force. The most considerable variation in the amount of solar energy reaching the surface of the earth is the difference between the amount of energy received at the poles and the amount of energy received at the equator. This difference is mainly due to the angle at which the rays of the sun strike the Earth. In equatorial areas where the rays of the sun hit the surface nearly straight on, the water and ground receive more heat per area compared to polar regions where the rays hit at more of an angle. Consequently, the ground in equatorial regions is warmer and transfers more heat to the atmosphere. Since the earth always tries to maintain an energy balance, heat is transferred from warmer areas to cooler areas.

Air density is related to temperature, such that warm air is less dense than cold air. On a small scale, this density difference leads to the creation of local wind patterns and on a larger scale, it leads to the formation of areas of low and high atmospheric pressure. The most common example of this is the land/sea breeze in coastal areas. This same process also occurs on a global scale. When the air in equatorial areas becomes less dense and warmer than the surrounding air, it rises to be substituted by air flowing in from cooler areas. Similarly, the very cold air in polar regions sinks toward the surface because it is more dense and colder than surrounding air. This process establishes a large convection cell in which dense, cold air descends toward the Earth's surface at the poles, becomes warmer as it passes over the surface headed for the equator, and eventually rises when it has become less dense and warm at the equator. This flow, called the Hadley circulation, is the way things might work were it not for the earth's rotation. As air travels over the earth's surface it is diverted from its original path due to the rotation of the earth. This occurrence is known as the Coriolis Effect. This effect classifies the earth's surface winds into three main wind belts or cells within each hemisphere: easterly trade winds dominate in an area covering the equator to a latitude of about 30 degrees north or south. The westerly winds are prevalent from 30 degrees to about 60 degrees, while the polar easterly winds prevail in the area from 60 degrees to the pole. Figure 1-2, taken from the European Space Agency (ESA), shows these wind patterns.

It can be stated however that overall, wind patterns at particular locations follow repetitive trends. Though year to year annual variations in wind speed remain difficult to predict because wind is driven by the sun and the ensuing seasonal variations, wind patterns tend to recur over the period of a year (Patel, 2005). They can thus be readily described in terms of a probability distribution. For a lot of sites, in northern Europe especially, wind speed variations throughout a year are best described using the Weibull distribution. According to Johnson (2001), two parameters can be used to describe this distribution. The shape parameter 'k' that ranges from 1 to 3 and is related to the mean wind speed at the site and 'c' the scale parameter that depends on the above-mentioned k-factor. The mainstream form of the Weibull distribution function for wind speed can be described by its cumulative distribution function $F(V)$ and probability density function $f(V)$ as given in Equation 1.1 and 1.2 (Johnson, 2001).

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} for\ 0 < v < \infty \tag{1.1}$$

$$F(V) = 1 - e^{-\left(\frac{v}{c}\right)^k} \tag{1.2}$$

The *k* and *c* parameters can be obtained using the mean wind speed-standard deviation method given in Equations 1.3 and 1.4 below.

$$k = \left(\frac{\sigma}{\bar{\upsilon}}\right)^{-1.086} (1 \leq k \leq 10) \tag{1.3}$$

$$c = \frac{\bar{\upsilon}}{\Gamma(1 + {}^{1}/_{k})} \tag{1.4}$$

Where $\bar{\upsilon}$ is the mean wind speed calculated using Equation 1.5, and σ is the standard deviation calculated using Equation 1.6.

$$\bar{\upsilon} = \frac{1}{n}\left[\sum_{i=1}^{n} v_i\right] \tag{1.5}$$

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{\upsilon})^2\right]^{1/2} \tag{1.6}$$

Where *n* is the number of hours in the time period considered such as season, month or year.

Γ is the gamma function and using the Stirling approximation, the gamma function of (*x*) can be given as follows:

$$\Gamma(x) = \int_0^\infty e^{-u} u^{x-1} du \tag{1.7}$$

The described wind patterns can thus be used to provide an assessment of the energy that might be accessible for extraction from a given site.

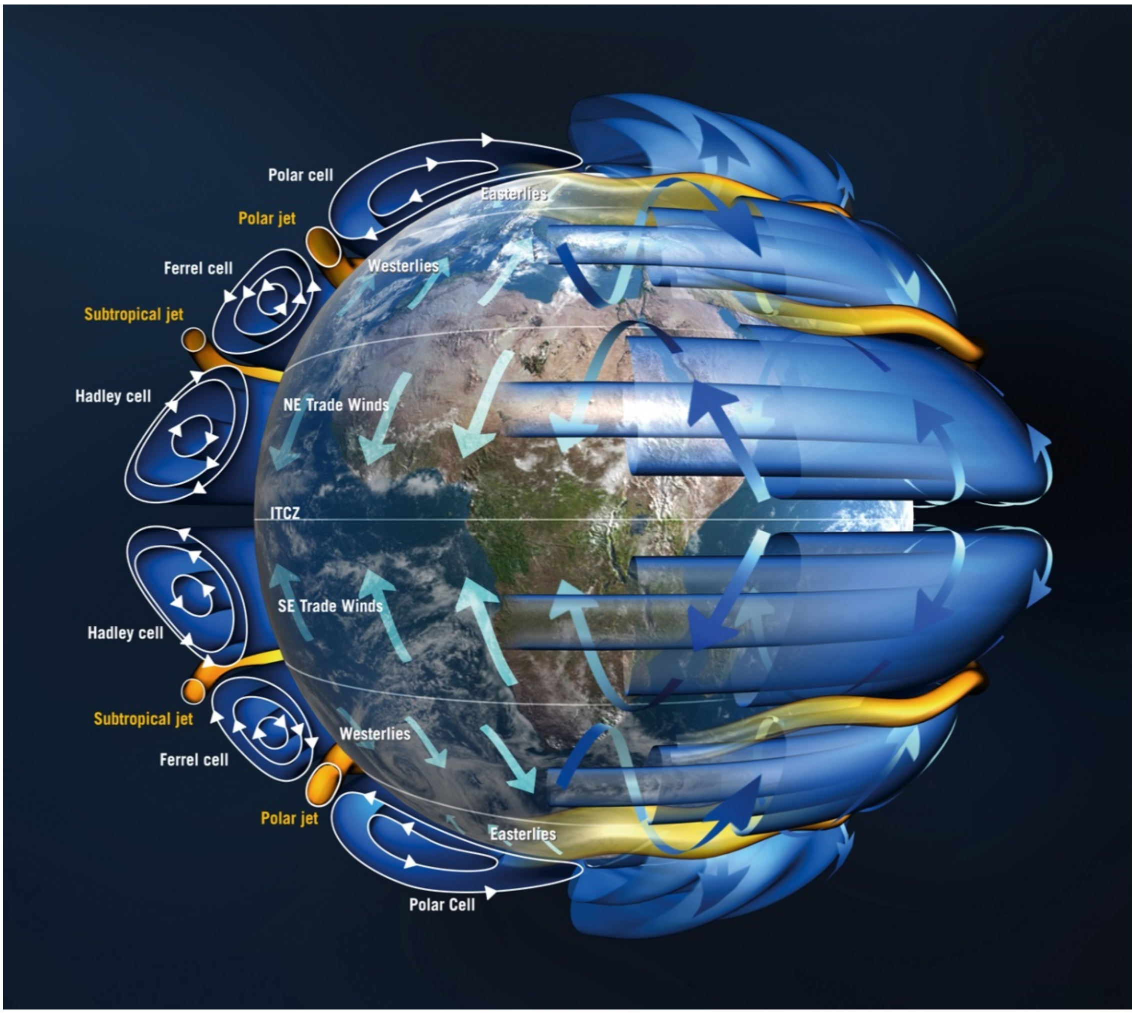


Figure 1-2. Earth’s wind patterns (ESA, 2015)

1.3.2 The History and Development of Wind Turbines

The technology of wind energy made its initial actual first steps centuries ago with the vertical axis windmills, in the period around 200 BC, found at the Persian-Afghan borders and the horizontal-axis windmills of the Mediterranean and the Netherlands following much later (1300 - 1875 AD) (Fleming and Probert, 1984; Kaldellis and Zafirakis, 2011). The introduction of the earliest horizontal-axis windmill using the principles of aerodynamic lift instead of drag may have taken place in the 12th century. These designs operated in the Americas and throughout Europe into the present century. The 700 years since the first wing turbine saw craftsmen discovering a lot of the operational and practical structural rules without comprehension of the physics behind them. These principles were not clearly understood until the 19th century. In the USA during the 19th century, further development and perfection of wind turbine systems was performed, i.e. between 1850 and 1970 over 6 million small wind turbines were used for pumping water (Dodge, 2001). The need for a water pump was driven by the extraordinary growth of agriculture in the Midwest beginning with the opening, in the early 1800s, of the north western prairie states.

Research into wind turbine use specifically for electricity generation was embarked on in various locations, including Denmark, Scotland and the USA, from the late 19th century onwards (Johnson 2001). In 1888 the Brush wind turbine in the USA had produced 12 kW of direct current (DC) power for battery charging at variable speed (Carlin et al., 2003). In 1925, Joseph and Marcelleus Jacobs commenced work on the first truly affordable, small-size, battery-charging, high-speed, turbine. Thousands of these 32 and 110 V DC machines were manufactured beginning in the late 1920s and running into the 1950s. Further to the development of wind generators in the USA, countries in Europe (the U.K, Germany, France and Denmark) were designing and building innovative wind turbines. In Denmark, the Gedser mill 200 kW three-bladed upwind rotor wind turbine successfully operated until the early 1960s (Meyer, 1995). In Germany, a string of advanced horizontal-axis wind turbine designs were developed dictating future horizontal-axis design approaches which later emerged in the 1970s (Kaldellis and Zafirakis, 2011).

The most significant milestones in the history of wind energy coincide with the involvement of the U.S government in wind energy research and development after the 1973 oil crisis (de Carmoy, 1978; Thomas and Robbins, 1980; Gipe, 1991). In the following years between 1973 and 1986, the commercial wind turbine market evolved from agricultural and domestic (1 - 25 kW), to utility interconnected wind farm applications (50 - 600 kW). It is this context that ushered in the first large-scale wind energy penetration outbreak in California as a result of the incentives given by the United States government. On the other hand in northern Europe, wind farm installations gradually increased through the 1980s and the 1990s, with the excellent wind resources and the higher cost of electricity leading to the creation of a small but stable market (Kaldellis and Zafirakis, 2011). Most of the market activity shifted to Europe after 1990 (Ackermann and Söder, 2002), with the last 30 years bringing wind turbines to the forefront of the global scene.

Wind turbines are generally defined as machines that capture kinetic energy in the wind through the force it applies on its blades, converting it to rotational energy which is then used for electricity generation (Gipe, 1991). There are two types of wind turbines: horizontal axis and vertical axis. The oldest wind turbines were Vertical axis wind turbines (VAWT). According to Hau (2003), various versions of this turbine design, the Darrieus, H-rotor and Savonius, have been produced. In the Darrieus design, the blades rotate and are shaped in the pattern of a surface line on a turning rope with a vertical axis of rotation. The H-rotor is a variation of the Darrieus design and instead of curved rotor blades, straight blades connected to the rotor shaft by struts are used. The Savonius design uses drag to rotate and is used occasionally for simple, small wind rotors. The advantage of VAWT concepts is their design simplicity which includes the possibility of housing generator, gearbox and electrical and mechanical components at ground level and the absence of a yaw system. The major disadvantage of this design is its low tip-speed ratio, not being able to control speed or power output by pitching the rotor blades and inability of self-start.

The Horizontal Axis Wind Turbine (HAWT) is the dominant design in wind energy technology today. In this design the drive train, generator and rotor axis are placed inside the nacelle at the top of the tower. The superiority of this design is largely based on controlled rotor speed and power output by pitching the rotor blades about their longitudinal axis, ability of the rotor blade shape to be aerodynamically optimized, and a higher coefficient of performance compared to the VAWT (Hau, 2003). The disadvantages of this design include the associated losses due to the response time between changes in wind direction and the expense and difficulty associated with tower installation.

Early developers grouped wind turbines together in order to allow for greater energy extraction from a given area creating wind farms. The years since then have seen the sizes of wind turbines on wind farms increase from measured rotor diameters of approximately 15 m - 50 m with outputs of a few hundred kilowatts, to sizes of between 1.5 MW and 3 MW with rotor diameters greater than 100 m (IEA, 2013). A similar trend was also seen in early wind farms in terms of output. While initially farms consisted of several turbines producing less than 2 MW, recent wind farm developments consist of large numbers of turbines resulting in outputs of several hundred megawatts. Most of the significant developments stated above have taken place onshore until recently. Since the early 1990’s however, interest grew in large-scale offshore deployment with the installation of the first offshore farm in Denmark. By the end of 2012, 5.4 GW had been installed (up from 1.5 GW in 2008), mainly in Denmark (1 GW) and the United Kingdom (3 GW), with large offshore wind power plants installed in Sweden, Netherlands, Belgium, Germany and China (IEA, 2013).

1.4 Purpose for the Comparative Study of Wind Turbine Design Variations

The previous sections have highlighted the general reasons that make the assessment of wind energy technologies necessary by outlining the historical development of the sector and the current drivers for change. The following section seeks to illustrate the need for the comparative assessment of wind turbine design variations investigated in this work.

1.4.1 Drivers of Future Wind Energy Performance and Cost Reductions

A number of market-based and technological drivers are expected to determine whether projections of future costs and performance for wind turbine systems are ultimately realized (Lantz et al., 2012b). Performance improvements related with continued turbine design advancements and upscaling are projected, and lower capital costs may be achievable. According to Lantz et al. (2012a), possible technical drivers include enhanced real-time controls capabilities and increased reliability, as well as reduced component loading through a combination of improved materials. Increased reliability is expected to minimize turbine downtime and reduce operations expenditures, while reduced component loading is expected to encourage continued cost effective turbine scaling (e.g. growth in rotor diameter, hub heights and machine rating). Innovations in logistics challenges and manufacturing improvements are also expected to further reduce the cost of wind energy (Lantz et al., 2012a).

The scope of future wind turbine performance and cost reductions is however highly uncertain. Although costs are expected to decrease into the future, resurgence in the demand for wind turbines could counter these cost reductions (Lantz et al., 2012b). Sustained movement toward sites with lower wind speed may also inescapably increase industry-wide Lifecycle Cost of Energy (LCOE), despite technological improvements (Lantz et al., 2012a). Increasing competition among manufacturers on the other hand could drive down the LCOE of onshore wind energy to a greater extent than envisioned (Lantz et al., 2012a). It is therefore clear that the coming years represent an opportunity to improve and modernise wind turbines, taking into account the environmental and economic aspects that may be amassed long into the future. This calls for a comprehensive and thorough sustainability assessment of wind turbine design options.

1.5 Research Aims, Objectives and Novelty

The aim of this research is to identify the most sustainable wind turbine design option for grid electricity supply taking into account environmental, data uncertainty propagation and economic aspects within the context of sustainable development. It is hoped therefore that the results and conclusions of this assessment can contribute to an informed debate on the implications of using the wind turbine design options in question and hence, their suitability in tackling the aforementioned environmental issues. The specific objectives of this research have been:

- To undertake a review and critically examine existing literature on the subject. This includes academic and industrial sources, as well as any other sources considered appropriate;
- To develop an integrated methodology to enable identification of the most sustainable wind turbine design option;
- To develop a life-cycle model for an existing wind turbine (as a baseline scenario) and to evaluate the environmental, data uncertainty propagation and economic aspects;
- To identify projections of potential performance for wind turbine systems. These include performance improvements related with continued wind turbine design advancements and upscaling;
- To develop possible scenarios for wind turbine systems with an outlook to the future and to evaluate these considering the environmental, data uncertainty propagation and economic aspects; and
- To identify the most sustainable wind turbine design option considering the different sustainability indicators.

As far as the author is aware, this is the first study of its kind for wind turbine design variations. The main novelty of the study is in the following outputs:

- An integrated methodology for sustainability assessment of wind turbine design variations – although focused on wind turbines is also applicable to other renewable technologies;
- Scenario development to identify projections of potential performance improvements for wind turbine systems;
- First ever analysis of wind turbine design variations using a hybrid DQI-statistical method for uncertainty analysis; and

- Life cycle environmental and economic assessment of the different wind turbine design variations.

1.6 Publications

Journal Papers

Ozoemena, M., R. Hasan and W. M. Cheung (2016). "*Analysis of technology improvement opportunities for a 1.5 MW wind turbine using a hybrid stochastic approach in life cycle assessment*." Renewable Energy 93: 369-382.

Ozoemena, M., Cheung, W.M. and Hasan, R. "*Comparative LCA of technology improvement opportunities for a 1.5 MW wind turbine in the context of an onshore wind farm located in South Wales, UK.*" to be submitted to International Journal of Life Cycle Assessment**, Impact Factor 3.988, (Q1)**

Conference Papers

Ozoemena, M., Cheung, W.M., Hasan, R. and Fargani, H. (2016) "*A hybrid Stochastic Approach for Improving LCA Uncertainty Analysis in the Design and Development of a Wind Turbine*". 9th International Conference on Digital Enterprise Technology - DET 2016 – Intelligent Manufacturing in the Knowledge Economy Era, CIRP Procedia, March 2016, Nanjing, China.

Ozoemena, M., Cheung, W.M., Hasan, R. and Hackney, P.M. (2014) "*A hybrid Data Quality Indicator and statistical method for improving uncertainty analysis in LCA of a small off-grid wind turbine*". In: ARCOM Doctoral Workshop on Sustainable Urban Retrofit and Technologies, 19 June 2014, London South Bank University.

Ozoemena, M., Cheung, W.M., Hasan, R. and Hackney, P.M. (2013) "*A Review of Life Cycle Assessment of Renewable Energy Systems*". International Conference on Manufacturing Research, 19-20 September 2013, Cranfield University, UK. Pages 649 - 654.

1.7 Thesis Structure

The thesis is structured in the following way: Chapter 2 discusses the findings of the literature review while the sustainability assessment methodology is the subject of Chapter 3. Chapter 4 describes the main concepts governing wind farm design while Chapter 5 outlines the basic theory behind wind power utilization and illustrates how the wind farm model used for the comparison was created. Chapter 6 discusses results of the uncertainty analysis, life cycle environmental impacts and economic assessment. Finally, Chapter 7 provides conclusions, makes policy recommendations and proposes future work.

Chapter 2 Review of Existing Assessments for Energy Supply Systems

The sustainability of energy supply systems has been the subject of several studies in recent years. These studies have assessed a broad range of issues covering environmental sustainability as well as economic and social implications. This chapter provides an overview of previous contributions to the field making it possible to identify gaps in the current literature which this research seeks to address. As a first step in Section 2.1, existing methodologies that can be applied to the analysis of energy supply systems are reviewed, beginning with the general history of these techniques and a description of their initial fields of application. Following this, the focus of Section 2.2 then moves on to the introduction of uncertainty which is a fundamental concept underlying this thesis. Finally in Section 2.3, relevant research on the environmental and economic aspects of wind energy is presented and critiqued resulting in the identification of areas where further work could be beneficial. It is the findings from this review that this research seeks to address.

2.1 Existing Methodologies for Environmental Impact Assessment

2.1.1 Energy Analysis

Energy analysis is a method for calculating the total amount of energy necessary to provide a service or a good (Mortimer 1991). During recent decades energy analysis has attracted increasing attention especially after the 1973 oil crisis. After the initial confusion regarding the number of different methodologies and nomenclature used, participants at a conference in 1974, held by the International Federation of Institutes for Advanced Studies (IFIAS), agreed on a general framework which included terminology, conventions, procedural aspects and analyses which is commonly limited to energy according to the first law of thermodynamics (Hovelius and Hansson, 1999).

The interactions between the economy and energy analysis have been discussed by several authors. The 1971 publication of the book “Power, environment and society” by Howard Odum (Odum, 1971) in which he proposed that energy and money flow along the same paths but in opposite directions encouraged a number of researchers, among them Scheuer, Saxena, Worrell, Engin and Khurana to illustrate the energy requirements of cement production (Scheuer and Ellerbrock, 1992; Saxena et al., 1995; Worrell et al., 2000; Khurana et al., 2002; Engin and Ari, 2005; Hasanbeigi et al. 2010; Xu et al., 2012). Slesser and Leach examined the costs of food production (Leach, 1975b; Slesser, 1978; Tilman et al., 2009; Bazilian et al., 2011; Pimentel, 2012) while Chapman, Rashad, Hammand and Lenzen extended the use of the methodology to the nuclear power industry where they focused on the energy requirements of nuclear power stations (Chapman, 1974; Chapman and Mortimer, 1974; Chapman, 1975; Rashad and Hammad, 2000; Lenzen, 2008). Georgescu-Roegen (1975) also made a link-up between thermodynamics and the economy, especially with the concept of entropy where he tried to integrate physics, energetics and economy. The interface between ecology and economy has also been analysed by some biophysicists (Hall et al., 1986; Cleveland, 1991) who argue that today's economic system does not satisfactorily reflect natural resource scarcity. It became apparent that the methodology could be used to evaluate and inform policies and large scale projects resulting in its growth into a tool for assessing complex systems, from biological systems to engineering designs, which allowed a detailed analysis of a systems inputs and outputs (Hammond, 2007).

Energy analysis has traditionally been critiqued from many points of view. The criticism is with regards the suitability of using energy alone as a measure for resource use, along with the fact that energy is not an unambiguous concept in the sense that different forms of energy can be totalled (Nilsson, 1997). Likewise, the statement that all processes transform energy is indisputable according to fundamental thermodynamics. It is important to note that since the original guidelines at the IFIAS conference, a lot of conventions were changed due to the need for an emphasis on different objectives.

2.1.2 Exergy Analysis

Exergy analysis is a method that uses the conservation of energy and conservation of mass principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems (Dincer, 2002). It is a useful tool for advancing the goal of energy resource use efficiency as it enables the type, locations and true magnitudes of waste to be determined. Exergy analysis therefore reveals whether or not and by how much it is possible to design energy systems that are more efficient by reducing sources of inefficiency in existing systems (Rosen and Dincer, 1997).

The concept of exergy is widely recognized today as having its roots in early work that would later become classical thermodynamics when in 1824, Carnot stated that "*the work that can be extracted of a heat engine is proportional to the temperature* *difference between the hot and the cold reservoir*". Thirty years later this simple statement led to the position of the second law of thermodynamics (Sciubba and Wall, 2007). According to Bejan (2002), the development and expansion of mature exergy theory in the 1970's and the growth of its applications were as a result of two influential causes. One is the stimulating, clear and concise discussion presented by some textbooks of the 1960's that encouraged generations of Engineering Thermodynamics graduate students to enter the field, and the other is the "oil crisis" of 1973 that forced industries and governmental agencies in industrialized countries to concentrate on energy savings. Consequently, several researchers suggested exergy as the best way to link environmental impact and the second law because it is a measure of the departure of the state of a system from that of the environment (Szargut, 1980; Ahrendts, 1980; Wepfer and Gaggioli, 1980; Edgerton, 1982).

Exergy analysis has been applied to energy supply systems, including wind turbines, as can be seen in the works of Koroneos, Koca, Singh, Kotas and others (Singh et al., 2000; Koroneos et al., 2003; Koca et al., 2008; Aljundi, 2009; Kotas., 2013). It has also been applied to whole systems and national economies as illustrated in works by Ji, Hammond, Ertesvåg, Dincer and others (Hammond and Stapleton, 2001; Ertesvåg, 2001; Dincer et al., 2004; Ertesvåg, 2005; Ji and Chen, 2006). Though exergy analysis has its advantages for thermodynamic systems evaluation, Hammond (2004) argues that the link between environmental aspects such as pollutant emissions, resource utilisation and exergy is indirect and as a result does not provide enough basis for environmental appraisal. Exergy has also been applied to a number of areas with different methods. Gong and Wall (2001) notes that results from these methods are not immediately comparable and identifies lack of data as a common problem in most studies. A pragmatic conclusion would be the development of general guidelines and making available data suitable for exergy studies.

2.1.3 Net Energy Analysis (NEA)

According to Cleveland and Costanza (2007), net energy analysis seeks to assess the direct and indirect energy required in the production of a unit of energy. Direct energy is the electricity or fuel used directly in the generation or extraction of a unit of energy. Indirect energy is the energy used elsewhere in the economy to produce the goods and services used in the extraction or generation of energy. It is the total energy cost of particular goods and services (Bullard et al., 1978).

Net energy concerns heightened in the 1970s and early 1980s following the energy crisis/ oil embargo years of 1973 and 1979–1980. As a result several NEA studies have covered oil made from coal or extracted from oil shale and tar sands, solar electricity from orbiting satellites, biomass plantations, geothermal sources, nuclear electricity and alcohol fuels from grain (Pilati, 1977; Herendeen et al., 1979; Whipple, 1980; Spreng, 1988; Herendeen, 1988; Knapp et al., 2000; Schmer et al., 2008; Kubiszewski et al., 2010; Razon and Tan, 2011; Pai, 2012). In 1974, Federal legislation requiring NEA of federally supported energy facilities was passed. It required that *‘‘the potential for production of net energy by the proposed technology at the state of commercial application shall be analyzed and considered in evaluating proposals’’* (Public Law No. 93-577, Sect. 5(a) cited in Herendeen, 1998). Particularly, the aim reflected the suspicion that certain technologies might result in being net energy consumers rather than producers. NEA provided a means of directly comparing a technology's energy output with the energy required to create it. Such an assessment, it was believed, provided the ultimate test for any new technology. If a technology consumed more energy than it produced (thus having a negative net energy value), the technology cannot provide any valuable contribution to energy supplies and would be regarded as a "net energy sink". Equally, if the technology produced more energy than it consumed, then it should be adopted even with an unfavourable economic evaluation.

The main criticism of NEA is related to the fact that it is an elusive concept subject to various inherent, generic problems that make its application complicated. These problems persist not because they are unstudied, but because they reflect underlying ambiguities that can only be removed by judgmental decision (Herendeen, and Cleveland, 2004). The problem of comparison between energy types of different thermodynamic qualities, density, and ease of storage, the question of how to compare energy consumed and produced at different times and the difficulties associated with specifying a system boundary all make NEA more difficult to perform and interpret. These objections attacked the very basis of NEA which assumes that the human/economic life-support system can be separated into the ‘‘energy system’’ and the ‘‘rest of the system’’ and that studying the energy system as a separate entity is valid (Herendeen and Cleveland, 2004). This leads some analysts to thus reject net energy analysis and support energy analysis.

2.1.4 Life Cycle Assessment (LCA)

"Life Cycle Assessment refers to the process of compiling and evaluating the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006b). Consoli (1993) describes LCA as a process for evaluating the environmental burdens linked with a product, activity or process by identifying and quantifying materials and energy used and wastes released to the environment.

The concept of exploring a product's life cycle or function initially developed in the United States in the 1950's and 60's within the realm of public purchasing. The life cycle concept was first mentioned in a 1959 report by the RAND Corporation which focused on *Life Cycle Analysis* of the costs of weapons systems (Curran, 2012). Life Cycle Analysis (not referred to yet as 'Assessment') became the tool for better budget management which linked functionality to total cost of ownership. The conceptual leap from life cycle cost analysis to the earliest life cycle-based energy and waste analysis, and then to the wider environmental LCA (how LCA is viewed today) was made through a series of small steps. The well-known Coca Cola study from 1969 documented in Hunt et al., (1996), compared reusable versus disposable beverage containers. The environmental focus of the study, termed Resource and Environmental Profile Analyses (REPA), was on waste management and resource use not the wide-ranging environmental aspects that are now common in LCA.

The broad conceptual leap to environmental LCA as compared to Life Cycle Analysis of cost was made in the 1980's and formalized in the 1990's with the standardization in the 14040 Series of the International Organisation for Standardisation (ISO) and work of the Society of Environmental Toxicology And Chemistry (SETAC) leading to the further development of LCA as a methodological tool in its own right (Curran, 2012). LCA, as shown in Figure 2-1, involves four phases: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a;b). These guidelines influenced and were used in life cycle impact studies of energy generating systems as well as various products, as can be seen in works by the International Atomic Energy Agency (IAEA, 1994; IAEA, 1996), and ExternE projects of the European Commission (CEC and ETSU, 1995). A third organisation has influenced the development of LCA since the end of the 1990's; the United Nations Environment Programme (UNEP). In 2002, this organisation started collaboration with SETAC in the UNEP/SETAC Life-Cycle Initiative, which aims to bring LCA and other life-cycle approaches into practice through stakeholders in developing countries. Studies on the application and theory of LCA has been undertaken by industry in the form of product “Eco-labelling” as well as various scholars (Pehnt, 2006; Thomassen, 2008; Roberts et al., 2009; Cherubini and Strømman, 2011; Peng, 2013; Uddin and Kumar, 2014).

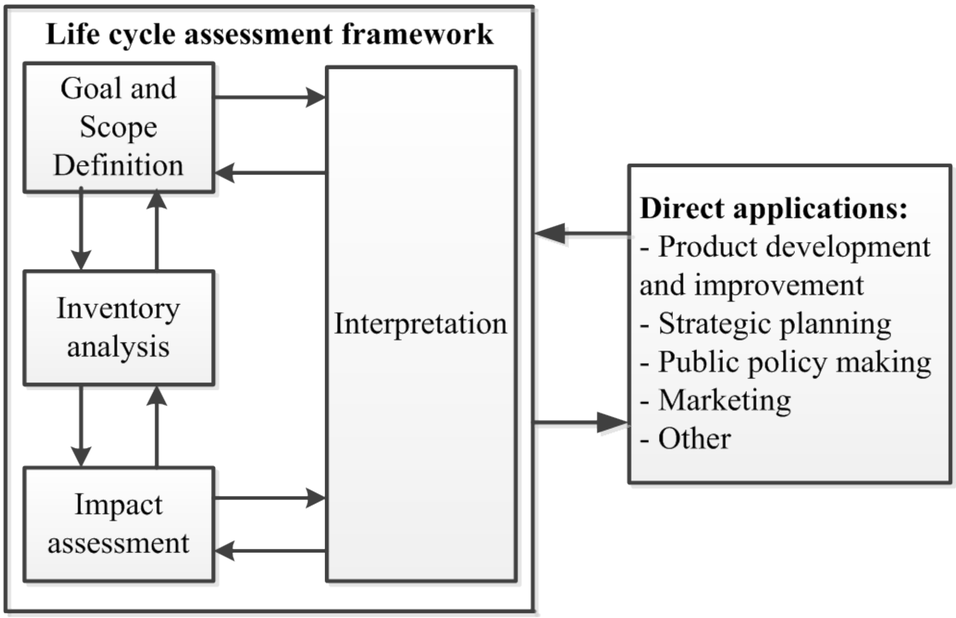


Figure 2-1. LCA framework and applications (ISO, 2006b).

From the beginning LCA methodology has covered the supply chain, use stage, and wastes processing from all stages, including end-of-life of the analysed product. It has become a tool that is important for informing environmental policy making and now is normally used to communicate environmental performance results. LCA however, like all real-world systems simulation methodologies, has its limitations. Despite the existence of ISO standards 14040–14044 (ISO, 1997; ISO, 2006a;b), literature widely recognizes that life cycle assessment suffers from several methodological weaknesses. Data gaps, system boundaries and truncation, aggregation over time and space, treatment of electricity, treatment of co-products and treatment of biogenic carbon are identified as key methodological issues in Weidema (1993), Finnveden (1999), Weidema (2000), Ekvall and Finnveden (2001), Björklund (2002), Delucchi (2004), Zamagni et al. (2008), Reap et al. (2008), Kendall et al. (2009), Finnveden et al. (2009), Guinée, et al. (2009) and Delucchi (2010). Consequently, LCA is incapable of producing a single, categorical description of a products environmental footprint. Rather, each LCA study is an individual analysis based on a variety of approximations, simplifications, analyst choices and many uncertainties.

2.1.4.1 Attributional versus Consequential LCA

Of recent, LCA has been broadly classified into two different approaches: attributional and consequential (Frischknecht, 1998; Weidema, 2003; Brander et al., 2008; Neupane et al., 2011). According to ISO 2006b, an attributional LCA (ALCA) inventories and analyzes the direct environmental effects of a certain quantity of a particular service or product, recursively including the direct effects of all necessary inputs across the supply chain, as well as direct effects of the use and disposal of a product. ALCA generally describes the average operation of a static system regardless of policy or economic context (Plevin et al., 2014). Hence ALCA does not model impacts as a result of production changes in the output of a product.

In contrast, "*consequential LCA (CLCA) estimates how flows to and from the environment would be affected by different potential decisions*" (Curran et al. 2005). CLCA models the underlying relationships as a result of the decision to change a product's output, and accordingly seeks to advise policy makers on the wider implications of policies which are intended to change levels of production (Brander et al., 2008). While ALCA is context independent, static and average, CLCA ideally is marginal, context specific and dynamic.

Although there is still debate on the appropriate uses of CLCA and ALCA, many studies have determined that the main difference is that CLCA estimates the effects of a certain action while ALCA does not (Curran et al. 2005; Ekvall and Andrae, 2006; Whitefoot et al., 2011; Reinhard and Zah, 2011; Earles and Halog, 2011). Because CLCA is intended to estimate the effect of an action or decision, it can assist as a guide to mitigation potential. Results of a CLCA, as with ALCA, varies with the modeller's subjective methodological choices, such as how specifically to model consequences, for example, whether to use general or partial economic models and how these models are parameterized and configured (Khanna and Crago, 2012). By introducing dynamic relationships among elements of a system and expanding the scope of the analysis, CLCA introduces an added level of structural model uncertainty making it more useful for examining different scenarios to understand the range of possible environmental consequences than for predicting a single most-likely consequence (Ekvall et al., 2007; Delucchi, 2011; Sathre et al., 2012; Zamagni et al., 2012).

The number of LCA studies published using a consequential approach has increased in recent years, with studies on product price differences, wind power, milk production, soybean meal, vegetable oils and biofuels-induced land use change appearing in literature (Thiesen et al., 2008; Pehnt et al., 2008; Thomassen et al., 2008; Dalgaard et al., 2008; Schmidt and Weidema, 2008; Kløverpris et al., 2008; Reinhard and Zah, 2009; Schmidt, 2008; 2010). However apart from Kløverpris et al. (2008) and Pehnt et al. (2008), none of the other studies apply economic models. The other studies rather assume that a single marginal product and supplier can be identified.

The distinction between ALCA and CLCA is an example of how choices in defining the goal and scope of an LCA should influence data choices and methodology for the life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases. Guinée (2002) identifies three important questions related to three important types of decisions in LCA modelling: strategic choices (concerning how to supply a function for an indefinite or long period of time), structural choices (concerning a function that is supplied regularly), and occasional choices (relating to one-off fulfilment of a function). These different decisions may necessitate different types of data and different types of modelling (consequential or attributional) since they have different scales in terms of impacts and time.

The basis of LCA methodology requires data collection about the system under examination and comparison and calculation of flows within the assessed boundary conditions. A number of methods can be used in LCA to carry out this comparison and collection of flows, the most prominent of which are described below.

2.1.4.2 Process Analysis

Process analysis encompasses the tracing of the energy inputs to all the services and products on which a process depends, described mainly in physical terms (Mortimer 1991). Process-based LCI models are created using a bottom-up approach, and generally describe and define activities in physical terms. As is typical of bottom-up modelling approaches, process-LCI enables data use that is specific to the individual operations being modelled; therefore it has the potential to achieve high levels of specificity and support detailed analyses (Lenzen and Dey, 2000). The appearance of process-based LCA can be traced back to the 1970's within energy analyses of industrial systems (Chapman 1974a; Boustead and Hancock 1979). The process analysis approach is best suited to analysing specific processes where energy and material flows are well documented as it allows a segmental approach and the optimization of individual life cycle processes. A major limitation of process-LCI models is that their representations of real product systems are generally incomplete (Lenzen and Dey, 2000; Suh and Huppes, 2005; Strømman et al., 2006; Majeau-Bettez et al., 2011), which occurs because there is a boundary to the number of individual processes that can be accounted for in a bottom-up approach. Efforts by some studies to quantify the cumulative importance of missing components in process-LCIs have been inconclusive. Majeau-Bettez et al. (2011) however notes that process based LCI approaches fail to account for 30% or more of entire inventories.

2.1.4.3 Input-Output Analysis (I/O)

I/O analysis is a macro-economic method that assesses the environmental emissions and economic inputs of an entire economic sector (Lenzen and Dey, 2000). I/O-based LCI models are top-down representations of economies, collected and supplied by the statistical agencies of national governments, holding data on transactions between economic sectors as well as resource use and pollution that occur in the sectors (Miller and Blair, 2009). In this manner, the life cycle emissions and associated impacts of a product can be calculated by associating the monetary value added during a life cycle stage to the emissions and associated impacts of a particular economic sector. According to Rebitzer et al., (2004), I/O analysis was developed in 1936 by Wassily Leontief who published US tables for the years 1919 and 1929. In the mid 1980's, the general method was presented comprehensively (Miller and Blair, 1985) along with a review of environmental and energy-based I/O extensions. However, while the I/O approach is more comprehensive in assessing upstream impacts, it lacks the detail required to make a distinction between individual products such as specific fuel pathways (Hendrickson et al., 2006; Heijungs et al., 2006). It also assumes that environmental effects and expenditures are linearly related, which is likely a poor assumption in fast growing and developing sectors (Reap et al., 2008).

2.1.4.4 Hybrid Analysis

Hybrid analysis attempts to combine the benefits of process and I/O analysis in such a way that the advantages of both approaches – i.e. the extensive coverage of product systems facilitated by I/O analysis and the high precision level of process analysis – are exploited. To achieve this, I/O-based LCI should be used to model activities that would otherwise have been omitted and process-based LCI to model important activities. A number of studies have proposed different techniques to combine I/O-based and process-based perspectives in a way that results in compactible interaction, as seen in *path exchange* (Treloar, 1997; Lenzen and Crawford, 2009), *waste input-output* (Nakamura and Kondo, 2002; Kondo and Nakamura, 2004), *integrated* (Suh et al., 2004), *tiered* (Strømman et al., 2009) and input-output-based (Suh et al., 2004) hybrid analysis. These methods however are highly complex as it is essential to ensure that the boundary conditions used by each one of the two merged methodologies match.

2.1.5 Section Conclusion

From the literature it can be seen that the reviewed methodologies provide a basis for the environmental appraisal of energy supply systems though their respective links to various environmental impacts is open to debate. This supports statements made by Nilsson (1997), Hammond (2004) and Herendeen and Cleveland (2004) that the results from these different methods are not directly comparable. Methodological weaknesses such as system boundaries and truncation, aggregation over time and space, comparison of energy produced and consumed at different times and lack of data have also been identified in the discussed literature as key issues. Therefore the adoption of a specific methodology is subject to various inherent factors making comparisons complicated.

2.2 Uncertainty

Model building is a process of simplification, extrapolation and approximation, resulting in differences between the processes modelled and modelled results (Krupnick et al., 2006). The fact that models are imperfect and their results uncertain is not a matter of controversy. When the results from a model however form the basis for decision making, it becomes important to understand whether and how the uncertainty affects the decision (Morgan et al., 1992; Krupnick et al., 2006). This thus requires uncertainty analysis. This section discusses the types of uncertainty encountered in models and the methods for propagating these uncertainties through to the results of a model.

2.2.1 Types of Uncertainty

Several researchers have developed different typologies to categorize uncertainty (Morgan et al., 1992; Cullen and Frey, 1999; Krupnick et al., 2006; Refsgaard et al., 2007; Lloyd and Ries, 2007). The primary difference among the types of uncertainty is generally agreed to be between: (i) lack of knowledge, which comprises parameter and model uncertainty; (ii) variability resulting from heterogeneity of a quantity in a population, and across space or time; (iii) decision uncertainty, which are introduced by modelling choices that reflect the judgement of decision makers about how results of a model are interpreted e.g., choices regarding time horizons and decisions about risk tolerance (Krupnick et al., 2006). Figure 2-2 illustrates the typology of uncertainties as illustrated in Krupnick et al. (2006).

2.2.1.1 Lack of Knowledge

Lack of knowledge (also known as epistemic uncertainty) in the typology presented here is divided into two categories: model and parameter uncertainty. Parameter uncertainty, like variability, applies to empirical quantities only and results from a lack of understanding of the quantity of interest. Unlike variability, parameter uncertainty may be reduced through further investigation (Krupnick et al., 2006). It is due to difficulties or errors in either applying data or measuring data from the measured source to the modelled variable.

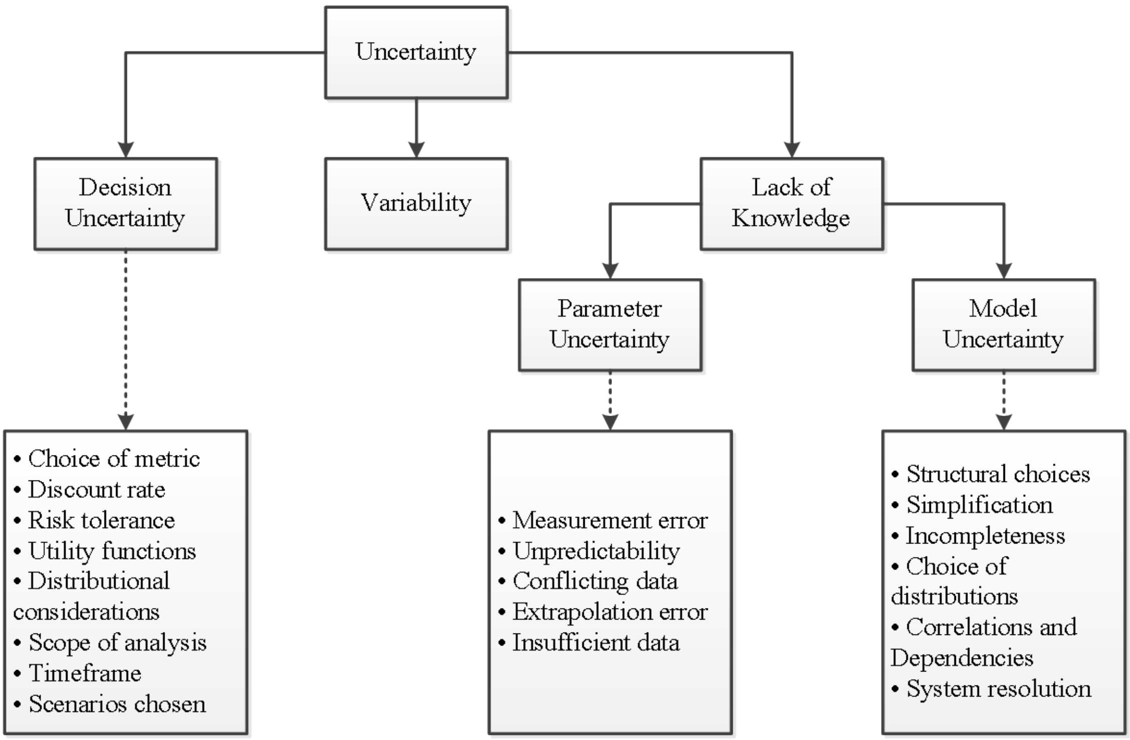


Figure 2-2. Typology of uncertainties (Krupnick et al., 2006)

Model uncertainty is also considered epistemic, informative, or subjective uncertainty and it is due to a lack of knowledge about choices that determine model behaviour or to system behaviour (van Asselt, 1999). While parameter uncertainty results from practical data limitations, model uncertainty is as a result of limitations in the ability to build predictive or causal models of real-world systems on the basis of the data (Krupnick et al., 2006). Errors are initiated by methodological difficulties in approximating a system and results from ignorance about the actual behaviour of the system.

2.2.1.2 Variability

Variability occurs when an empirical quantity that could be measured as a single point value actually exists in a population of values, varying across individuals, time, or across space (Krupnick et al., 2006). Variability is referred to using many other names in the literature, including aleatory, objective, ontological, stochastic, and process uncertainty. The requirement in a model to choose a single point value to represent this heterogeneity results in uncertainty. Variability cannot be mitigated through further research but could be handled through disaggregation in a model (Krupnick et al., 2006). This type of uncertainty is however easier to represent accurately given data availability from which statistics can be derived.

2.2.1.3 Decision Uncertainty

It is stated in Finkel (1990) that decision uncertainty arises whenever there is controversy or ambiguity about how to compare or quantify social objectives. These uncertainties resulting from choices in methodology cannot be eradicated but could be made operational with the aid of cultural theory perspectives, probabilistic simulation and scenario analysis (Zamagni et al., 2008). Whereas model uncertainty, parameter uncertainty, and variability are issues for risk assessors, decision uncertainties are concerns primarily for risk managers (Krupnick et al., 2006). Decision uncertainties are very important because they go to the basis of how social objectives are determined (Krupnick et al., 2006).

2.2.2 Uncertainty Analysis

According to Morgan et al. (1992) and Krupnick et al. (2006), decision-makers relying on models should be acquainted with the uncertainty surrounding model results. Of key significance is an understanding of the range of outcomes from model results that would result in different decisions. In the context of regulation, overlooking uncertainty can provide a false perception of difference among alternatives (Weidema, 2000; Basson and Petrie, 2007), which can result in regulations that promote consequences contrary to those envisioned, or worse, that fail to achieve their goals (Cherubini et al., 2009). Some well-understood and generally accepted methods used to propagate uncertainty are described as follows:

2.2.2.1 Analytical Method

Analytical methods are based upon the use of distinct mathematical expressions for the distributions of the model results (Heijungs and Huijbregts, 2004). Ciroth et al. (2004) and Hong et al. (2010) give Taylor series expansion as the main procedure for the analytical method. Taylor's first order approximation, also referred to as "Gaussian error propagation formula" is regularly used in uncertainty quantification of an underlying model. It is a mathematical technique that has been used in uncertainty analyses to estimate the deviation of an output variable (Δy) from the deviation of its input variables (Δx_i) (Hong et al., 2010). That is, output variances are calculated based on input variances through Gaussian approximation (Equation 2.1) (Heijungs, 1996).

Assuming a variable *y* depends on a number of variablesx_1, x_2,…., and the functional relationship is denoted by *f*:

$$y = f(x_1, x_2, \dots) \tag{2.1}$$

The propagation of absolute errors in the variables x_1, x_2, …, indicated by Δx_1, Δx_2,…, into the dependent variable *y*, is given by:

$$\Delta y \ = \left|\frac{\partial f}{\partial x_1}\right| \Delta x_1 + \left|\frac{\partial f}{\partial x_2}\right| \Delta x_2 + \dots \tag{2.2}$$

This equation can be used to derive a similar equation for propagating the variance var(x_1), var(x_2), ..:

$$var\ (y) \ = \left(\frac{\partial f}{\partial x_1}\right)^2 var(x_1) + \left(\frac{\partial f}{\partial x_2}\right)^2 var(x_2) + \dots \tag{2.3}$$

The connection with the standard deviations σ(x_1), σ(x_2), … is then made using the fact that the variance is the square of the standard deviation:

$$\sigma(y) = \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 \left(\sigma(x_1)\right)^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 \left(\sigma(x_2)\right)^2 + \dots} \tag{2.4}$$

Distribution-free variances of input parameters can then be used to calculate the variances of output variables (Heijungs and Huijbregts, 2004). Analytical methods are based on the approximation of the moments of distributions (Morgan et al., 1992). The variance of the second moment in particular is used in a first order Taylor approximation (Heijungs and Huijbregts, 2004). Hence only the variance (or standard deviation), not the distribution, is required. Less information is therefore needed for analytical methods compared to stochastic methods.

2.2.2.2 Stochastic Simulation

Stochastic simulation varies the input data of a calculation according to the probability distribution given, runs the calculation and stores the output/outcome data of the calculation (Ciroth et al., 2004). Monte Carlo Simulation is the most well-known form of this approach. The procedure is repeated enough times, typically hundreds to thousands of model evaluations depending on the required precision, in order to ensure the obtainability of input values that sufficiently represent the selected probability distribution. Thus for a function$f(x) = y$, one simulation run may be expressed as in Equation 2.5:

$$f(x) = f(x_t + \Delta x) = y_t + \Delta y = y \qquad (2.5)$$

Where,
Δx: Error in *x*
x_t: True value for *x*,
x: Measured/observed value for variable *x*,
Δy: Error in *y*,
y: Observed/calculated value for variable y
y_t: True value for *y*

If the input data for each parameter is drawn from a particular distribution, the results will vary from run to run and consequently lead to a sample of results, whose statistical properties may be investigated (Heijungs and Huijbregts, 2004). Thus, compared to analytical methods, Monte Carlo Simulation provides improved accuracy about the uncertainty in calculation results. Ciroth et al. (2004) however notes that Monte Carlo Simulation cannot correct ill-specified input uncertainties and it does not tell what to do with the uncertainty that it calculates. Simulating all parameter inputs could easily exceed available time and computer resources owing to long solution times making this a key limitation of Monte Carlo Simulation.

2.2.2.3 Sensitivity Analysis

Saltelli et al. (2008) defines sensitivity analysis as the study of how uncertainty in a model output can be assigned to different sources of uncertainty in the input of a model.

Local and global sensitivity analyses are identified in Saltelli et al. (2008) as the two main approaches for examining model uncertainty. In local sensitivity analysis one model parameter at a time is altered while keeping other parameters at their nominal value and the change in model results observed. Though widely used, this approach largely underestimates the uncertainty in a model. Saltelli et al. (2006) argues for the use of local sensitivity analysis in strictly linear models since in models that are nonlinear, the sensitivity to any single factor largely depends on the state of other variables. Consequently identified model output ranges, when altering single parameters, will underestimate the possible range when model parameters are varied simultaneously.

Global sensitivity analysis, on the other hand, examines the influence of individual parameters to the model output overall uncertainty while allowing all parameters to vary. A common method for global sensitivity analysis uses the results of a Monte Carlo simulation (discussed above) to account for the rank correlations between input and output parameters across the span of selected input values in the simulation. This type of breakdown identifies the (usually few) parameters that have the most contribution to the variance, and hence where research might be most beneficial to reduce uncertainty (Morgan et al., 1992). The advantages of global sensitivity analysis are identified in Cariboni et al. (2007) as: (i) the identification of factors that may perhaps be further investigated to reduce the uncertainty and (ii) the identification of factors with negligible contribution to the total variance, thus allowing for model simplification by treating those factors as certain.

2.2.2.4 Fuzzy Set Theory

Fuzzy theory provides a means by which subjective or incomplete information can be represented in an analytical form (Penmetsa and Grandhi, 2003). In fuzzy set theory, the variability is described by the membership function which can be obtained based on expert opinion or available information and the input parameter is treated as a fuzzy number (Suresh et al., 1996). The membership function of each fuzzy set is generally assumed to be a trapezoidal or triangular function and is treated as a possibility distribution (Suresh et al., 1996). The key advantage of fuzzy set theory is that it can accommodate the confidence levels of variables (Penmetsa and Grandhi, 2003). It is highlighted in Urbanski and Wąsowski (2003) that the operation of averaging series of data does not decrease uncertainty. This is therefore a limitation of fuzzy set theory.

2.2.3 Uncertainty in LCA

LCA literature is full with studies that make no effort to quantify uncertainty. Numerous reviews of how uncertainty is handled in LCA have come to the conclusion that uncertainty is generally handled poorly (Björklund, 2002; Ross et al., 2002; Heijungs and Huijbregts, 2004; Lloyd and Ries, 2007). According to Lloyd and Ries (2007), Finnveden et al. (2009) and de Koning et al. (2010), only parameter uncertainty is considered in most analyses of uncertainty in LCA. Besides variability and data gaps, there is debate regarding appropriate co-product treatment in LCA that result in unresolved model uncertainty (Delucchi, 2004), whether to use a different aggregation period or existing standard 100-year global warming potentials (ISO, 2006b), and there is model uncertainty surrounding estimates of GHGs (Brakkee et al., 2008). The literature is awash with debates of the challenges uncertainty presents (Huijbregts, 1998; Lenzen, 2000; Ross et al., 2002; Björklund, 2002; Heijungs and Huijbregts, 2004; Ciroth et al., 2004; ISO, 2006b; Lloyd and Ries, 2007; Reap et al., 2008; Finnveden et al., 2009; Weidema, 2009; Liska and Perrin, 2009). Despite the comprehensive acknowledgment of the significance of uncertainty in LCA, uncertainty is still ignored in many studies creating an impression of precision (Weidema, 2009).

2.2.3.1 Data Quality Assessment

Uncertainty in LCI is generally evaluated using two different approaches (van den Berg et al., 1999): the qualitative indicator method and the probability distribution function method. The first approach allows for dealing with poorly described data, data from unknown sources or missing data, while the second approach allows for the quantitative evaluation of specific parameter groups. The use of both methods is recommended for the evaluation of uncertainty in LCI. The qualitative indicator method consists of describing the characteristics of the data in question and designating a score to them. To do this, a "Pedigree Matrix" is established in which each column corresponds to a score ranging from poor to good, and each row corresponds to an attribute of the data. A basic approach of the use of data quality indicators (DQIs) and data quality management is shown in Weidema & Wesnaes (1996). They presented a procedure with the use of 5 data quality indicators and a pedigree matrix for measuring the following attributes:

- Geographical, technological and temporal correlations (in comparison with the data quality goals),

- Reliability of the data (assessment of the verification procedures and sampling methods),
- Completeness of the data (statistical representativeness).

The DQIs are semi-quantitative numbers which represent data quality and may be used to assess the reliability of the quality of the data collected with regard to the data quality goals (van den Berg et al., 1999). For the use of DQIs, LCI data is assessed for each DQI and assigned a semi-quantitative indicator score (Lloyd and Ries, 2007). They could also be used to identify sources of data uncertainty. This is highlighted in Lloyd and Ries (2007) where semi-quantitative DQI scores are translated into probability distributions using predefined uncertainty parameters. A certain DQI score corresponded with an uncertainty range which was then applied to the value of the parameter to generate the distribution. Academics carrying out these studies have warned against the direct use of DQIs because they represent data quality as opposed to the amount of uncertainty, and predefined uncertainty parameters are usually a lot smaller than those obtained with actual LCA data.

2.2.3.2 Uncertainty Propagation in Wind Energy LCA

In the wind energy LCA studies surveyed, stochastic and scenario modelling methods were used to propagate uncertainty. Majority of the studies employed scenario modelling to propagate uncertainty on LCA outcomes (Martínez et al., 2009; Tremeac and Meunier, 2009; Martínez et al., 2010; Zhong et al., 2011; Guezuraga et al., 2012; Padey et al., 2012; Greening and Azapagic, 2013; Demir and Taşkın, 2013; Garrett and Rønde, 2013; Zimmermann, 2013; Oebels and Pacca, 2013; Uddin and Kumar, 2014; Aso and Cheung, 2015), while three of the studies (Khan et al., 2005; Fleck and Huot, 2009; Kabir et al., 2012), employed stochastic modelling to propagate uncertainty. Of the 12 studies using scenario modelling, all assessed scenarios using sensitivity analysis. For the studies employing stochastic modelling, all used Monte Carlo Simulation with random sampling. Some studies however made no effort to quantify uncertainty (Allen et al., 2008; Weinzettel et al., 2009; Crawford, 2009).

2.2.4 Section Conclusion

Most studies in the literature used scenario modelling to make uncertainty operational in input parameters in order to compare outcomes for different alternatives. Scenario uncertainty was characterized through the development of unique scenarios while model and parameter uncertainty were generally characterized with probability distributions.

Characterization of uncertainty in wind energy LCA has been restrained by a lack of information as regards possible choices and input values. For more reliable results to be obtained, emphasis should be placed on accurately characterizing uncertainty and selecting appropriate distributions.

2.3 Life cycle Environmental and Economic Assessment of Wind Energy

The literature is full with wind power LCAs and it is a known fact that results differ considerably across studies, and the causes of the inconsistency are often difficult to extricate. The large availability of studies as well as the often unexplained variability in results presents a challenge for researchers looking to familiarize themselves with the literature. The following section describes the assembly of the literature archive which forms the basis of the review and survey.

2.3.1 Geographical Scope

It is stated in Lenzen and Wachsmann (2004) that while direct impacts are a distinctive attribute of a product or process, indirect impacts can be expected to vary with the performance and structure of the supplying background system that is, the economy of the site of production. Oebels and Pacca (2013) attributes the smaller total CO_2 intensity of a Brazilian wind farm, compared to previous wind power LCAs, to the Brazilian electricity supply mix which is mainly based on renewable energy sources (87% in 2010). Wang and Sun (2012) showed that large CO_2 savings can be made in countries with large territories and wind potential as a result of a case study of four characteristic wind power plants (one in China and three in North America and Europe) with Vestas 1.65 MW, 3.0 MW and 850 kW wind turbine models. Analysis of the case in China shows that 33% of CO_2 emissions could be saved in the transport stage in large countries by the use of shorter alternative transportation routes. Lenzen and Wachsmann (2004) demonstrates that an identical wind turbine manufactured in Germany and Brazil exhibits quite different pollutant and resource embodiments due to upstream supply chain effects which can only be assessed comprehensively when the background supply-system is sufficiently accounted for. Uddin and Kumar (2014) undertook life cycle environmental, emissions and embodied energy analysis for two grid connected rooftop wind turbines (500 W horizontal axis and 300 W vertical axis) considering their applications, industrial performance and associated issues in Thailand. Results show that per kWh/year energy delivered, the vertical axis wind turbine is more emission and energy intensive compared to the horizontal axis wind turbine. Energy payback time,

CO_2 emission intensity and energy intensity were established to be lower when compared with results from studies conducted in New Zealand, Australia, France and Austria.

2.3.2 Relative Contribution of Different Life Cycle Stages

Looking at the respective contributions from different stages of the life cycle to overall climate change and energy use results, the manufacturing stage dominates as is discussed in most wind turbine LCA studies (Fleck and Huot, 2009, Martinez et al. 2009, Guezuraga et al., 2012, Greening and Azapagic, 2013 and Zimmermann, 2013). It is clear that for onshore applications, the turbine itself is the most significant component with regards to GHG emissions and energy use followed by the foundation. The tower usually holds a share of 30-70% of the overall wind turbine indicator values. For offshore wind turbines, the foundation becomes rather more important as seen in Weinzettel et al. (2009) and Wagner et al. (2011). In general, emissions related to transportation are established to be of negligible importance. There are exceptions however as Tremeac and Meunier (2009) highlights a GHG emissions transportation contribution of 34%, which could be related to concrete as the choice of tower material as opposed to steel towers used in most studies. The end of life phase, if recycling is applied, normally yields substantial emissions reductions (Martinez et al., 2009; Tremeac and Meunier, 2009; Weinzettel et al., 2009; Chen et al., 2011). Recycling reduces the GHG emissions and energy embodied in a wind turbine, as shown in Martinez et al. (2009) and Chen et al. (2011), lowering the indicator values by 26-27%.

2.3.3 Effects of Wind Turbine Size

Studies done previously on LCAs of wind energy maintain economies of scale in the environmental impacts over the life cycle of wind energy systems. In Kubiszewski et al. (2010) and Raadal et al. (2011), there is evidence of GHG emissions and energy use decreasing with increase in the size of wind turbines. Demir and Taşkin (2013) provides useful evidence that environmental impacts are lower for larger turbines (2050 kW and 3020 kW) than smaller turbines (330 kW, 500 kW and 810 kW) and could be further reduced by installation in optimum wind speed regions. Results expressed per unit of produced electricity in Tremeac and Meunier (2009) show that across all categories, environmental damages are more important for the small wind turbine than for the large one. A comparison of three wind turbine configurations, one Northern Power (NP) 100 kW turbine, five Jacobs (JA) 20 kW turbines or twenty endurance (EN) 5 kW turbines to produce a nameplate power of 100 kW was carried out by Kabir et al. (2012). Life cycle energy and environment results show lesser impacts for the NP compared to JA and EN configuration. Crawford (2009) also shows that advantages exist for the use of a 3 MW wind turbine compared to an 850 kW turbine, such as the ability to decrease the environmental footprint per unit of rated output. The results of the survey show lower GHG emissions with higher wind turbine nameplate capacity. This confirms the existence of economies of scale for turbine sizes greater than 1 MW.

2.3.4 Future-Inclined Studies

Arvesen and Hertwich (2011) presents a global scenario based assessment that estimates 3.5 Gt CO_2e emitted as a result of operating and building wind farms in the time frame between 2007 and 2050 to supply 22% of electricity worldwide by 2050. A cohesive life cycle modelling of cumulative avoided emissions is also included in the same study. The results show that emissions avoided by wind energy exceed emissions caused by wind energy. In the 2008 NEEDS project report on offshore wind technology, assumptions are made on economies of scale and design changes in wind energy technologies in order to establish life cycle inventories for prospective offshore wind power systems. Pehnt et al. (2008) couples life cycle inventories with a stochastic model for the electricity market to study grid expansion, the life cycle CO_2 emissions of wind energy and energy storage using compression of air. The results for year 2020 show insignificant emissions from upgrades to the grid and storage, but a significant emission penalty of 18-70 gCO_2/kWh as a result of balancing variable electricity from wind with fossil fuelled power stations. In Lenzen and Schaeffer (2012), avoided and caused climate change impacts of eight energy technologies are analysed towards 2100, the main aim being to show differences between temperature based indicators for climate change mitigation potential and emissions. Da Silva (2010) proposed a mathematical framework for simulating the time dynamics in gross and net energy balances for deployments of wind energy. Computational results were shown to be favourable for wind energy.

2.3.5 Comparison with Other Electricity Generation Technologies

A study evaluating the environmental sustainability of micro-wind turbines in the UK in comparison with solar photovoltaic (PV) and grid electricity was conducted by Greening and Azapagic (2013). The results showed that wind turbines are more environmentally sustainable than solar PV for seven out of eleven impacts and the majority of environmental impacts from the wind turbines are lower than from grid electricity. Singh et al. (2011) estimates the life cycle GHG emissions of electricity from natural gas and coal with carbon capture and storage (CCS) to be 140 – 160 gCO_2e /kWh and 180 – 220 gCO_2e/kWh respectively. Without CCS the corresponding values are around 500 – 600 gCO_2e/kWh for natural gas and 1000 gCO_2e/kWh for coal. The figures show that wind energy's carbon footprint is considerably lower than that of power generation technologies with CCS that are fossil-based. Weinzettel et al. (2009) finds that in human toxicity impact categories a wind farm scores 2 – 6 times worse compared to a natural gas combined cycle plant. A wind farm is also noted in Wagner et al. (2011) to perform slightly worse than average German electricity mix as regards human toxicity. Other studies suggest that wind energy outperforms the average Spanish electricity mix (Martinez et al. 2009) and European mix (Vestas, 2006) with respect to human toxicity. A 2011 report by the IPCC presents the interquartile range for life cycle GHG emissions of wind energy as 8 – 20 gCO_2e/kWh. The corresponding ranges for competing technologies are 3 – 7 g/kWh for hydro, 8 – 45 g/kWh for nuclear, 29 – 80 g/kWh for solar PV and 14 – 32 g/kWh for concentrating solar PV. Similarly, comparisons of life cycle emissions of particulates, NWVOC, NOx and SO_2 of different power generation technologies indicate good environmental performance for wind energy (IPCC, 2011). A comparison of the environmental impacts of a 600 kW wind turbine and a polycrystalline PV module was conducted by Zhong et al. (2011). The study established smaller environmental impacts for the wind turbine in almost all assessed categories.

2.3.6 Economic Assessments

Kabir et al. (2012) carried out life cycle cost analysis of three wind turbine configurations, one Northern Power (NP) 100 kW turbine, five Jacobs (JA) 20 kW turbines and twenty endurance (EN) 5 kW turbines. The results show that at 10% internal rate of return, the price of electricity for NP is $0.21/kWh whereas, JA and EN prices are 16% and 65% higher respectively. Fleck and Huot (2009) employed life cycle cost to analyse a single-home diesel generator system and a stand-alone small wind turbine system. The net-present cost of the wind turbine system was shown to be 14% greater than the diesel system. An economic analysis of three wind turbines in Cuba having rated capacities of 275 kW, 750 kW and 850 kW was carried out by Prats et al. (2011). The results show that production costs per kWh of wind energy generated in Cuba is expensive due to its high price of generation since it is conditioned by high installation costs. Ozerdem et al. (2006) carried out economic and technical feasibility of wind farms in Turkey. The results indicate that the costs of energy generated by wind turbines with different characteristics are a function of the installed capacity. An economic and design assessment of a 20 MW wind farm in Saudi Arabia was carried out by Rehman et al. (2011). It is shown that the proposed wind farm could produce energy at $0.0294 per kW h. Present value cost and cost of energy results indicate that the wind farm development and its operation are feasible economically and requires due attention from investors and policy makers.

2.3.7 Section Conclusion

Despite variability in results of the reviewed studies, existing wind energy LCA research gives a fairly good overall understanding and provides numerous insights into the life cycle environmental and economic aspects of wind power. Lenzen and Wachsmann (2004) and Raadal et al. (2006) have noted that the large gap between high and low values limit the usefulness of results to decision makers, and that compliance with some standardized assumptions in future analyses would be advantageous. Hence due attention needs to be given to the confusion arising as a consequence of variability in results.

2.4 Chapter Conclusion

This review examined literature of energy supply system assessments using several different approaches to assess a broad range of issues with regards to sustainability. In order to identify gaps in the current literature, first, a review of four methods applied to energy supply system analysis was carried out in Section 2.1. Ensuing this, the types of uncertainty and the methods for propagating uncertainties through model results are discussed in Section 2.2. To close, studies on the environmental and economic implications of wind power deployment are analysed in Section 2.3. Based on the review conducted in this study, certain conclusions can be drawn.

The literature review revealed a variety of methods for sustainability assessment of electricity generation. In this work, LCA has been adopted as this methodology is generally accepted as the mainstream approach for environmental impact assessment of wind energy systems. It covers a wide range of impact categories which represent all aspects of the life cycles under investigation. The scope of this methodology is such that it covers a range of topics that are already or are expected to become dominant in the near future, hence providing a common basis of comparison for different energy sources.

Another conclusion from the review of available literature is that the DQI method used for evaluation of uncertainty in LCI has major limitations. Indicators for quality assessment are not comprehensive enough for measuring data quality of each unit process (Coulon et al., 1997; Rousseaux et al., 2001). Weidema and Wesnæs (1996), Kennedy et al. (1996) and Maurice et al. (2000) note that indicators are often treated equally in importance without weighting. Different indicators may also play different roles in the uncertainty of a single parameter (Maurice et al., 2000). Transforming DQI scores into probability distributions of input data and then simulating propagation of the uncertainty however provides a means to overcome the limitations of the qualitative indicator and probability distribution function method. Though the DQI presents an approach for uncertainty analysis it is based on the "rule of thumb" (Finnveden and Lindfors, 1998). Therefore for more reliable results, it is important that areas requiring better understanding are further investigated.

Regarding the issues addressed by the environmental effects of wind energy, it can be said that existing LCA research provides a lot of insights. Differences in existing studies could be attributed to discrepancies in key assumptions, systems studied, methodological differences and data inconsistencies. An area that has not received much attention until recently has been that of technology improvement opportunities for wind turbine systems. It can be seen that there are only a limited number of studies dealing with the environmental effects of design variations for a particular power rating. The inclusion of economic analysis in wind energy LCA studies is also noted to lack assessments in design variations for a particular power rating in the studies reviewed. As such the body of work addressing these aspects are limited hence, a need for more research in these areas.

Despite the quantity of publications in the field the debate regarding the environmental and economic implications of wind energy, the problems of uncertainty and confusion due to variability in results is still ongoing. This has necessitated further studies using a different approach for uncertainty quantification and new assumptions for prospective analyses that would be beneficial for the body of knowledge.

Chapter 3 Research Methodology

This chapter presents the methodological approach adopted for sustainability assessment of wind turbine design options for the current situation and potential technology improvement opportunities. The methodology includes an approach for propagating data uncertainty in wind energy LCA, life cycle assessment and economic analysis for an existing turbine and potential wind turbine designs in order to help identify the most sustainable design option. It also provides explanations of the conventions assumed to allow for the comparison of the different designs assessed in this work.

3.1 Integrated Methodology for Sustainability Assessment of the Current Situation and Potential Wind Turbine Technological Advancements

The first step in the methodology is definition of the goal and scope of the research as presented in Section 3.2. Definition of the scope involves specifying the boundaries of the system and the design variations to be considered. Next in Section 3.3, sustainability issues are identified followed by the selection and definition of associated sustainability indicators to allow sustainability assessments for the different design variations. In Section 3.4, projections of potential performance for a wind turbine system is identified. The completion of the aforementioned steps helps to ascertain data requirements so that data gathering can be carried out as part of the next stage presented in Section 3.5. This involves collection of environmental, economic and technical data. The data are then fed into different tools and models to enable the design variations to be evaluated on sustainability. Life cycle assessment has been used for the assessment of environmental sustainability, a hybrid DQI-statistical method has been used for data uncertainty propagation in LCA and Life Cycle Costing (LCC) has been used for the economic assessment. The respective methodologies for the environmental, data uncertainty propagation and economic assessments are outlined in Sections 3.6.1 - 3.6.3. The following sections describe the individual methodological steps in more detail following Figure 3-1.

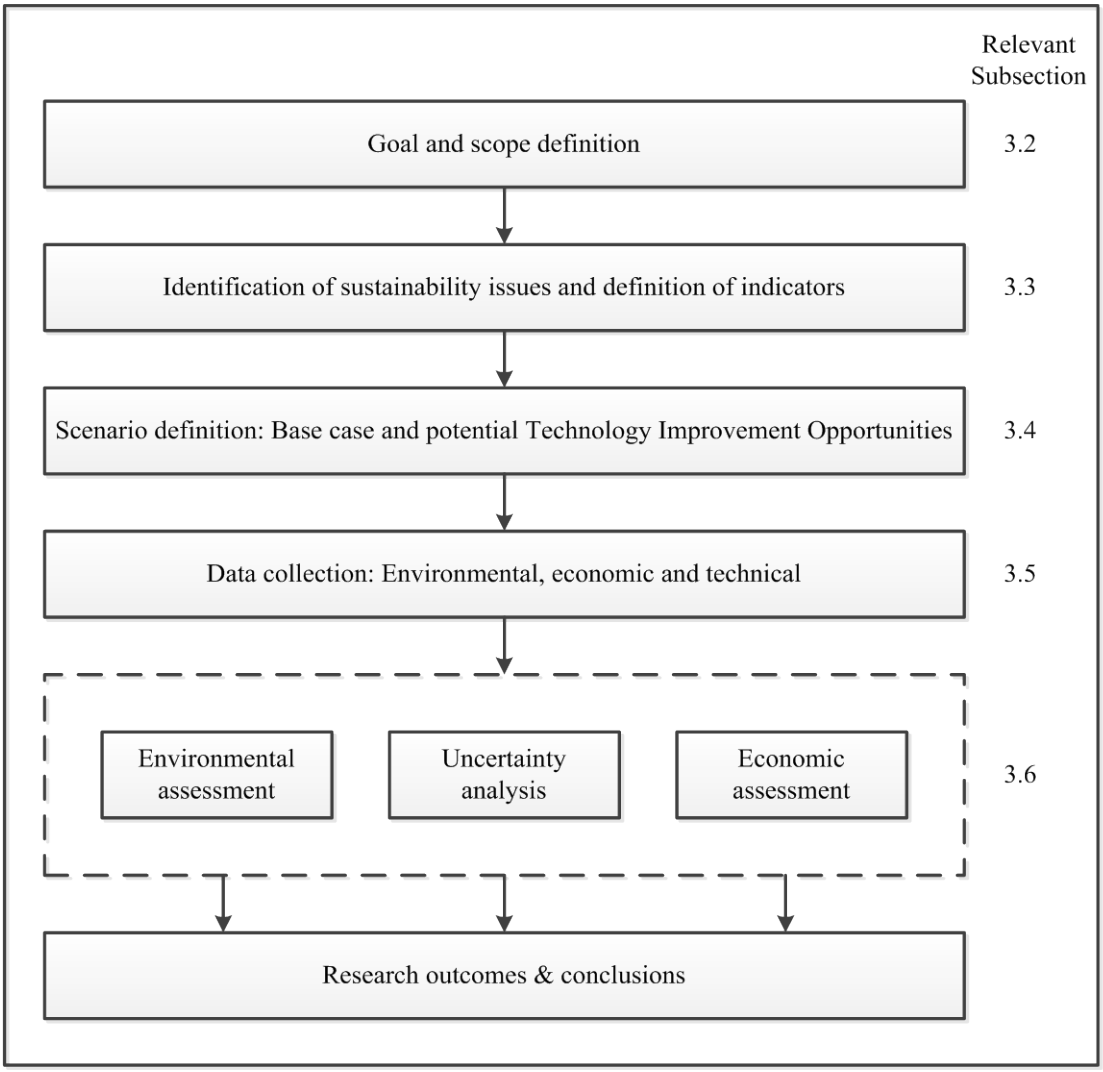


Figure 3-1. Integrated methodology for sustainability assessment of wind turbine design variations

3.2 Goal and Scope of the Study

The goal of this study is to present an analysis of wind turbine design options for grid electricity supply using a hybrid stochastic method to improve uncertainty analysis, life cycle assessment to assess environmental implications, and life cycle costing to evaluate the economics of the different design variations in order to determine the most sustainable design option. The motivation for this work is primarily due to the potential for technological advancements to reduce the cost and increase the performance of wind turbines. The system boundary for the uncertainty analysis in this work is drawn from 'cradle-to-gate' considering activities from raw materials extraction until the product leaves the factory gate. For the wind farm environmental assessment, certainty is assumed and the system boundary is drawn from 'gate-to-grave' considering all activities from wind plant set up, site operation and end-of life. Certainty is also assumed for the economic assessment which comprises the construction and operation of the wind farm with the exception of decommissioning.

3.3 Identification of Sustainability Indicators and Issues

Sustainability indicators used to compare the different turbine designs have been selected following the current environmental, energy and broader sustainability drivers at the international and national levels (IAEA, 2005; May and Brennan, 2006; IEA/OECD, 2008; Greenpeace and EREC, 2008a;b; Stamford and Azapagic, 2011; Gujba et al., 2010; 2011). The indicators and issues described in literature served as a guide and have been adapted to conditions in the U.K (as discussed later in Chapter 5).

The environmental indicators used in this study are those normally considered in LCA. These indicators have also been used in other energy system LCA studies (May and Brennan, 2006; Tremeac and Meunier, 2009; Weinzettel et al., 2009; Gujba et al., 2010; 2011; Stamford and Azapagic, 2011; Raadal et al., 2011; Greening and Azapagic, 2013). An overview of the LCA methodology is given in Section 3.6.1; for the definitions of LCA impacts see Appendix B.

The indicators for the uncertainty aspect considered here are the estimates of embodied energy and embodied carbon. These aspects are of considerable concern when assessing the sustainability of wind energy producing options (Martinez et al., 2009; Fleck and Huot, 2009; Chen et al., 2011; Kabir et al., 2012; Guezuraga et al., 2012; Uddin and Kumar, 2014). The description of these indicators is presented in Section 3.6.2.

For the economic sustainability assessment, the economic indicator payback period has been selected. It involves the estimation of capital investment cost, operations and maintenance (O&M) cost and revenue. The methodology for estimating these costs are outlined in Section 3.6.3. This indicator is used to compare the cost of generation for the different design variations to give some clue of the appeal of investing in different design options.

3.4 Scenario Definition: Baseline Case and Potential Technology Improvement Opportunities

Scenario analysis appeared in response to the limitations of forecasting methods to forward planning and it was established as a means of investigating possible projections which may or may not happen (Dreborg, 1996; Robinson, 2003). In the 1970's, Shell first used scenario development for energy analysis and it has since become one of the major tools for addressing the uncertainty and complexity characteristic of long-term strategy development in the energy sector (Kowalski et al., 2009). Therefore projections of future technological designs as a result of research and scientific developments, based on National Renewable Energy Laboratory (NREL) 1.5 MW wind turbine technology forecasting studies (Cohen et al., 2008 and Lantz et al., 2012), provided the basis for modelling future inventory changes. A summary of the potential for technology advancements to increase the performance of a 1.5 MW wind turbine is presented in Sections 3.4.2.1 – 3.4.2.4.

3.4.1 Baseline Turbine Characterization

To project advances in reliability and performance of wind turbine systems, a baseline 1.5 MW wind turbine technology must first be identified. This baseline technology will serve as a reference from which performance improvements are projected. The NREL's baseline turbine technology characteristics represent an upwind, variable-pitch, variable-speed, three-bladed turbine that uses a doubly fed generator rated at 1.5 MW. The height of the tower is 65 meters and the rotor diameter is 70 meters. As such, an Enercon E-66 1.5 MW turbine was chosen as it shares similar technical characteristics to the NREL baseline turbine.

3.4.2 Technology Improvement Opportunities (TIOs)

According to Cohen et al. (2008) and Lantz et al. (2012), identification of TIOs relied on judgements and technical insights of the senior research staff at the Sandia National Laboratories and National Wind Technology Centre at the NREL. The design of wind turbines is a matter of continuous compromise between the rival demands of greater energy productivity, lower cost, increased durability and lifetime, and maintenance cost. Realizing greater energy production may cost less or more. These are the designers' trade-offs captured in the model. Trade-offs between wind turbine components is dealt with in the estimation of the input parameters. The outcome of the details of the TIOs is summarized in the following sections.

3.4.2.1 TIO 1: Advanced (Enlarged) Rotors

Elongating the rotor in order to increase the capture of energy in ways that do not increase electrical power equipment or structural load requirements is the approach used in this TIO. Better energy capture from the same infrastructure investment is the end result. Several technological advances were used to create the ability to increase rotor diameter while reducing or maintaining total system installed cost. The identified areas are listed below, followed by some details of how each might affect energy production of the system.

- A combination of active and passive controls are used to reduce loads by 40% allowing for 20% rotor growth and 20% annual energy capture improvement. Improved pitch control and active speed can increase energy capture by another 5% resulting in an estimate of 25% rotor growth
- Heavier, longer blades would increase gravity loads on the entire system causing a considerable increase in capital cost. Therefore, stiffer carbon-fibre materials are used to reduce tip deflection and lighten the blade so that the full advantage of the loads reduction can be realized on the whole system and the annual energy production (AEP) can be improved without raising capital costs elsewhere but in the blades.
- Rotor mass reduction results in reductions in mass in the rest of the support structure, particularly in the tower, on the order of 2%.

3.4.2.2 TIO 2: Advanced Tower Concepts

This TIO is based on the use of new tower concepts that will facilitate higher towers to be built in more challenging locations, without needing usage of high lift capacity cranes and may allow on site tower assembly (and perhaps even fabrication), thereby decreasing tower transport costs. The key contrast is between the baseline tower and hub height at 65 meters, and the advanced tower and hub height at 100 meters. The advancement in this TIO is based on:

- New materials using carbon fibres

3.4.2.3 TIO 3: Drivetrain Improvements

The drivetrain of a wind turbine is generally composed of rotor brakes, a gear box, generators, and shafts that reinforce the rotor and their accompanying bearing. The approach chosen for considerably advancing the state of drivetrain technology is based on:

- **Single-Stage/Permanent Magnet Generators (PMGs):** This technology takes advantage of medium speed generators that spin at 150 rpm, compared to 1200 to 1800 rpm for standard induction generators. The designs of these generators are accompanied with a single-stage gearbox that is less complex (fewer gears and bearings) and much more compact than multi-stage gearboxes generally used in wind turbines. The permanent magnets in these generators, instead of copper wound rotors, further reduce their size and weight.

3.4.2.4 TIO 4: Fully Combined TIOs

This TIO combines all the above possible separate pathways within each TIO into a single inclusive TIO.

3.4.2.5 Mass Scaling Equations

To generate the material quantities for the different TIOs, information and scaling equations were taken from an NREL study (Fingersh et al., 2006). The report contained information about how the various components could be scaled using semi-empirical formulas. The equations used in this study are defined in Table 3-1 as well as an indication as to where they were employed.

Table 3-1. Mass scaling equations for the different components

Component	Equation	Description
Blade	$Baseline: Mass = 0.1452 \times R^{2.9158}\ per\ blade$ $Advanced: Mass = 0.4948 \times R^{2.53}\ per\ blade$	Where R = rotor radius. The advanced blade mass relationship follows products developed by a wind turbine blade manufacturer which “represents combinations of technology enhancements that may not/may include carbon and takes advantage of a lower-weight root design”.
Tower	$Baseline: Mass = 0.3973 \times \text{swept area} \times \text{hub height} - 1414$ $Advanced: Mass = 0.2694 \times \text{swept area} \times \text{hub height} + 1779$	The baseline case is based on conventional technology for 2002, while the advanced case represents advanced technologies including reduced blade solidity in conjunction with higher tip speeds, flap-twist coupling in the blade and tower feedback in the control system.
Generator	$Mass = 10.51 \times machine\ rating^{0.9223}$	A generator mass calculation for the medium-speed permanent-magnet generator design was based on machine power rating in kW.

Unlike most wind energy LCA scenario analyses which focused mainly on direct environmental impacts, this study takes an approach that considers not only the direct environmental impacts but also a range of other indicators for potential technology improvement opportunities for a wind turbine. As far as the author is aware, this is the first time such a study has been carried out for a 1.5 MW wind turbine.

3.5 Data Collection and Information Sources

This step of the research methodology involved data collection related to the environmental, economic and technical aspects of wind power. The work carried out in this thesis is based on information from publicly available reports that are industry and academia related, and registered databases compiled by international organisations and research institutes in relevant areas of research. Each section of this thesis discusses the information taken from reports as well as their references where used. Data collected for this research project were mainly taken from corporate and social responsibility reports, annual reviews, relevant publications from non-governmental organisations, industrial environmental statements and environmental organisations. Academic literature was also thoroughly reviewed and data from journal articles and peer-reviewed reports were incorporated into this work. The literature review provided information on the present status of wind energy, insights into industry standard practises, as well as operational data from currently operating facilities. Information from databases (Ecoinvent) compiled by research institutes was also used for other aspects of the modelling in this work. This information mainly consisted of data on the material and energy requirements for inputs to the systems. It was also used to complement information supplied in specialist literature (Hammond and Jones, 2008; 2011) where insufficient data in certain areas would have meant significant gaps in modelling of the subject matter.

Ecoinvent database v2.2 provided by the Swiss Centre for Life Cycle Studies is the main database used in this work (Dones et al. 2007). The database provides a set of unified and generic LCI data of high quality. The data are mainly based on Swiss and Western European conditions. The Ecoinvent database contains about 4100 datasets of products and services from the energy, transport, building materials, chemicals, pulp and paper, waste treatment and agricultural sector. The processes contained within the Ecoinvent database represent, generally, the average of technologies presently in operation. In this research, where some Ecoinvent database entries were felt to be unrepresentative of conditions in the U.K, they were modified accordingly.

3.6 Sustainability Assessment

The sustainability assessment carried out in this study has involved uncertainty analysis, environmental and economic assessment of the baseline and potential TIOs for a 1.5 MW wind turbine. The following sections outline the tools and methodologies used for each aspect of sustainability – LCA, data uncertainty propagation and economic costing.

3.6.1 LCA Methodology

LCA is a tool for environmental sustainability assessment used to quantify the environmental impacts over the life cycle of a system. It can be used for a variety of purposes, including identification of opportunities for improvements in a system or comparison of alternative systems (Perdon 2004; Baumann and Tillman, 2004). LCA methodology is standardised by the ISO standards (ISO 14040 and ISO14044) and as shown in Figure 2-1, it involves four phases: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a;b).

3.6.1.1 Goal and Scope Definition

The goal and scope definition phase defines the purpose of the study, the functional unit and the system boundaries. The purpose of the LCA study in this project is to compare and assess the environmental sustainability of different design variations for a 1.5 MW wind turbine in the context of a wind farm and the system boundaries are drawn from 'cradle to grave'. Therefore in order to create the model of each design, the process stages of each design need to be defined; this way inputs and outputs included within the scope of the lifecycle of each design variation can be highlighted and the environmental impacts from those processes can be ascribed to the final product of each design; the electricity they produce in this case.

The boundary of the wind farm includes the material production, site construction and components transportation, operation and maintenance requirements, and dismantling/decommissioning of components. The different stages of the wind farm life cycle (and their related boundaries) taken into account in the LCA are shown in Figure 3-2.

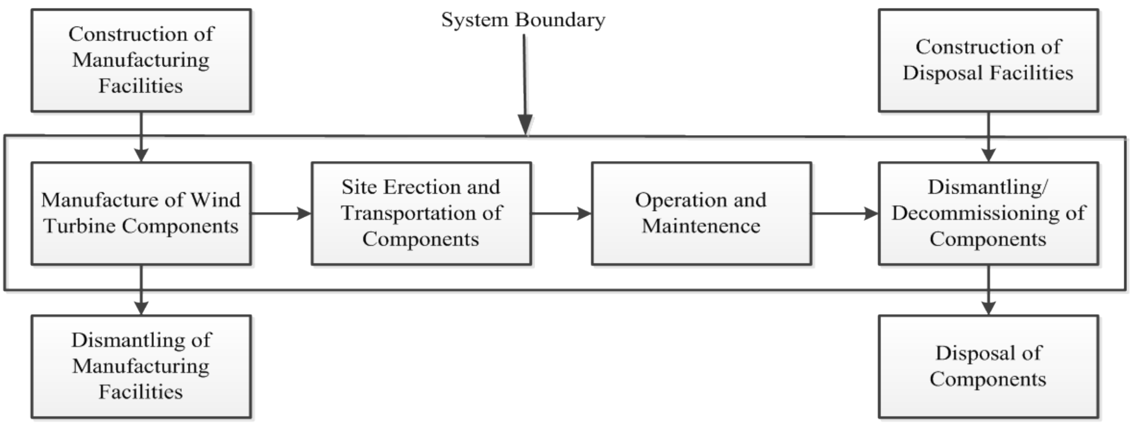


Figure 3-2. Boundary for the life cycle of the wind farm

According to the ISO 14040 standards (ISO 2006a), the functional unit can be defined as:

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

Since the purpose of the different wind turbine design variations is electricity production, the results of this study are based on the functional unit of:

"*The generation of 1 kWh of electricity delivered to the grid by a wind farm*"

All impacts are therefore estimated for this functional unit, making the results comparable with those of other assessments of energy technologies.

3.6.1.2 Life Cycle Inventory Analysis

Life cycle inventory analysis involves detailed description of the systems, data collection and quantification of environmental burdens. Burdens are defined as energy and materials used in the system and emissions to land, water and air. Azapagic et al. (2003) states that burdens describe the type of data necessary for collection for each part of the system and each life cycle stage which are then aggregated across the entire life cycle to calculate the burdens as given below:

$$B_u = \sum_{n=1}^{N} bc_{u,n} x_n \tag{3.1}$$

Where $bc_{u,n}$ is the burden coefficient related with the energy or material flow x_n in a process or activity. An example is given in Azapagic et al. (2003) where an emission of CO_2 (burden $bc_{u,n}$) is generated per tonne of natural gas (material flow x_i) used for electricity generation (activity or process). The same method is used in this study to calculate the burdens from the wind turbine design variations considered here.

3.6.1.3 Life Cycle Impact Assessment

In this phase the environmental burdens are translated into potential environmental impacts. ISO 14044 identifies four stages within impact assessment: i) impact classification, ii) characterisation, iii) normalisation, and iv) valuation (ISO, 2006b). The first two are compulsory while the last two are optional.

Impact classification involves assignment or aggregation of environmental burdens according to the type of environmental impact they contribute to. In LCA the impacts most often considered are related to ecological aspects, resource use and human health. These impacts are then classified into different impact categories, the most commonly considered of which include: aquatic and terrestrial ecotoxicity, ozone depletion, global warming, human toxicity, resource depletion, photochemical ozone formation, eutrophication and acidification (Perdon, 2004; Finnveden et al., 2009; Pehnt and Henkel, 2009). These impacts have all been considered in this study.

In the characterisation step the burdens calculated in the inventory phase are multiplied by a characterisation factor to determine a quantitative contribution of each burden to the appropriate impact categories as shown (Azapagic et al., 2003):

$$E_k = \sum_{u=1}^{U} ec_{k,u}\, B_u \tag{3.2}$$

Where $ec_{k,u}$ represents the contribution of burden or characterisation factor B_u to the impact E_k relative to a reference substance. For instance, IPCC (2007) gives the characterisation factor for CO_2 that quantifies its climate change contribution as 1kg CO_2eq./kg CO_2. Characterisation factors for N_2O and CH_4 are expressed relative to CO_2 and are 298 kg CO_2eq./kg N_2O, and 25 kg CO_2eq./kg CH_4 respectively.

A variety of methods can be used for the calculation of impacts in LCIA. In this study, the CML 2001 method has been used as it is one of the most extensively applied methods in LCA studies and is frequently updated as new LCI data and characterisation factors become available. It follows the approach expressed in Equation 3.2 and summarised above.

According to Azapagic et al. (2003), the impacts can also be normalised on the total impacts in a particular area over a given time period. Normalized results should however be interpreted carefully as the respective contributions from some impact categories at the regional and local scale (e.g. acidification and human toxicity) may look significantly smaller compared to total impact on a global scale (e.g. abiotic depletion, global warming) (Azapagic et al., 2003).

The last step of LCIA is valuation which involves weighting of different environmental impact categories which reflects the relative significance they are assigned in the study

(Finnveden et al., 2009). The multiple impacts are reduced to a single environmental impact function as a measure of environmental performance (Azapagic et al., 2003) as given:

$$EI = \sum_{k=1}^{k} w_k E_k \tag{3.3}$$

Where w_k is the weighting factor of the environmental impact E_k. For example, on a 1 to 10 scale each impact can be assigned a weight w_k from 1 to 10 indicating its importance in relation to other impacts. That is, the higher the score, the greater the importance of the impact to decision makers.

3.6.1.4 Interpretation

In the last phase of LCA, LCIA results are evaluated with the intention of drawing conclusions and proposing improvements. According to ISO (2006b), interpretation includes: identification of significant impacts and burdens in the system under study, sensitivity analysis, evaluation of results and final recommendations.

3.6.2 Data Uncertainty Quantification Model

Estimation of embodied carbon and energy is a significant part of life cycle assessments (Ortiz et al., 2009). Hammond and Jones (2008) defined embodied carbon (energy) of a material as the total carbon released (primary energy consumed) over its life cycle. This would normally encompass extraction, manufacturing and transportation. It has however become common practice to specify the embodied carbon (energy) as ‘Cradle-to-Gate’, which includes all carbon (energy – in primary form) until the product leaves the factory gate (Hammond and Jones, 2008). Ortiz et al. (2009) and Wang and Sun (2012) express embodied carbon and embodied energy mathematically as:

$$Embodied\ Carbon = \sum_{i=1}^{n} Q_i \times EF_i \tag{3.4}$$

$$Embodied\ Energy = \sum_{i=1}^{n} Q_i \times EEC_i \tag{3.5}$$

Where,

Q_i = Quantity of material *i*

EEC_i = Embodied energy coefficient of material $_i$

EF_i = Emission factor of material *i*

Since the purpose of the different wind turbine designs is electricity production, the functional unit is defined as 'generation of 1 KWh of electricity'.

Embodied carbon and energy are traditionally estimated deterministically using single fixed point values to generate single fixed point results (Lloyd and Ries, 2007). Lack of detailed production data and differences in production processes result in substantial variations in emission factor (EF) and embodied energy coefficient (EEC) values among different life cycle inventory (LCI) databases (Sugiyama et al., 2005; Wang and Shen, 2013). It is noted in Hammond and Jones (2008) that a comparison of selected values in these inventories would show a lot of similarities but also several differences. These variations termed as "data uncertainty" in Huijbregts (1998) significantly affects the results of embodied carbon and embodied energy LCA. Uncertainty is unfortunately part of embodied carbon and energy analysis and even data that is very reliable carries a natural level of uncertainty (Hammond and Jones, 2008; Kabir et al., 2012). Decision makers have different attitudes towards uncertainty or risk making information on uncertainty in LCA highly desired (Huijbregts, 1998; Sugiyama et al., 2005). The analysis of data uncertainty is therefore a significant improvement to the deterministic approach because it provides more information for decision making (Tan et al., 2002; Kabir et al., 2012; Wang and Shen, 2013).

Statistical and Data quality indicator (DQI) methods are used to estimate data uncertainty in LCA with different limitations and advantages (Lloyd and Ries, 2007; Wang and Shen, 2013). The statistical method uses a goodness of fit test to fit data samples characterizing data range with probabilistic distributions if sufficient data samples are available (Wang and Shen, 2013). On the other hand, the DQI method estimates data uncertainty and reliability based on expert knowledge and descriptive metadata e.g. source of data, geographical correlation of data etc. It is used quantitatively (Lloyd and Ries, 2007) and qualitatively (Junnila and Horvath, 2003; Lloyd and Ries, 2007). Compared to the statistical method the DQI costs less, although it is less accurate than the statistical method (Tan et al., 2002; Wang and Shen, 2013). The statistical method is preferred when high accuracy is required, though its implementation cost is high (Sugiyama et al., 2005; Wang and Shen, 2013). The DQI method is generally applied when the accuracy of the uncertainty estimate is not paramount, or the size of the data sample is not sufficient enough for significant statistical analysis (Wang and Shen, 2013).

Considering the trade-off between cost of implementation and accuracy, Wang and Shen (2013) presented an alternative stochastic solution using a hybrid DQI-statistical (HDS) approach to reduce the cost of the statistical method while improving the quality of the pure DQI method in whole-building embodied energy LCA. The study focused on the reliability of the HDS approach compared to the pure DQI without considering the effect of either approach on the decision making process. An application test case to the analysis of embodied energy and embodied carbon of potential 1.5 MW wind turbine technological advancements and the effect of these approaches on decision making is presented here to validate the presented solution. A description of the methodology is given below.

3.6.2.1 Qualitative DQI method

Qualitative DQI uses descriptive indicators, often arranged as a Data Quality Indicator (DQI) matrix (Table 3-2), to characterize data quality. Rows in the matrix represent a quality scale, ranging from 1 to 5 or 1 to 10. Columns represent data quality indicators such as age of the data, reliability of the data source etc. General quality for a data is specified by an aggregated number that takes into account all the indicators. For example if three indicators are assigned scores of (1, 3, 5) respectively for a given parameter, and the indicators are equally weighted, the parameter's aggregated DQI score is $P = 1 \times 1/3 + 3 \times 1/3 + 5 \times 1/3 = 3$.

Table 3-2. Data Quality Indicator (DQI) matrix based on Weidema and Wesnæs (1996), Junnila and Horvath (2003) and NETL (2010).

Quality Scale					
Data Quality Indicators	1	2	3	4	5
Data representativeness	Representativeness unknown or incomplete data from insufficient sample of sites and/or for a shorter period	Data from a smaller number of sites for a shorter period, or incomplete data from an adequate number of sites and periods	Representative data from an adequate number of sites but for a shorter period	Representative data from a smaller number of sites but for an adequate period	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations
Age	$\geq$15 years old	<15 years old	<10 years old	<6 years old	<3 years old
Acquisition method	Non-qualified estimation	Qualified estimation by experts	Calculated data partly based on assumptions	Calculated data based on measurements	Directly measured data
Supplier independence	Unverified information from enterprise interested in the study	Unverified information from irrelevant enterprise	Independent source but based on unverified information	Verified data from enterprise with interest in the study	Verified data from independent source
Geographical correlation	Unknown area	Data from an area with slightly similar production conditions	Data from an area with similar production conditions	Average data	Data from the exact area
Technological correlation	Data from process related of company with different technology	Data from process related of company with similar technology	Data from process studied of company with different technology	Data from process studied of company with similar technology	Data from process studied of the exact company with the exact technology
Rule of inclusion/ exclusion	Unknown	Non-transparent on exclusion but specification of inclusion	Transparent, not-justified, uneven application	Transparent, justified, uneven application	Transparent, justified, homogeneous application

3.6.2.2 Quantitative DQI method

This method transforms aggregated DQI scores into probability distributions to enable quantification of uncertainty using predefined uncertainty parameters. The DQI scores use a single rating to measure the overall quality of each data element. This rating is based upon a scale of one to five, with a one representing the worst quality (maximum uncertainty), and a five representing the best quality (minimum uncertainty) as shown in Table 3-3. These qualitative assessments are then used to parameterize the probability density function of a beta random variable *x* as shown in Equation (3.6):

$$f(x;\alpha,\beta,a,b) = \left[\frac{1}{b-a}\right]\left\{\frac{\Gamma(\alpha+\beta)}{[\Gamma(\alpha)\Gamma(\beta)]}\right\}\left[\frac{x-a}{b-a}\right]^{\alpha-1}\left[\frac{b-x}{b-a}\right]^{\beta-1} \qquad (3.6)$$

$$for\ (a \le x \le b);$$

Where α, β are shape parameters of the distribution, *a* and *b* are designated range endpoints, and *Γ* is the gamma function. The beta function is used due to the fact that "the range of end points and shape parameters allow practically any shape of probability distributions to be represented".

Table 3-3. Transformation matrix based on (Weidema and Wesnæs, 1996 and Canter et al., 2002).

Aggregated DQI scores	**Beta distribution function**	
	Shape parameters (α, β)	Range endpoints (+/- %)
5.0	(5, 5)	10
4.5	(4, 4)	15
4.0	(3, 3)	20
3.5	(2, 2)	25
3.0	(1, 1)	30
2.5	(1, 1)	35
2.0	(1, 1)	40
1.5	(1, 1)	45
1.0	(1, 1)	50

3.6.2.3 HDS approach

The HDS approach involves four steps: (i) Quantitative DQI with Monte Carlo simulation (MCS); (ii) Categorization of parameters; (iii) Detailed estimation of probability distributions for parameters; and (iv) Final MCS calculation. The parameter characterization identifies the critical parameters based on the influence and degree of uncertainty of the parameters. The final stochastic results are generated through a MCS calculation.

3.6.2.4 Quantitative DQI with MCS

This step begins with assessing data quality using the qualitative DQI approach. All parameters used for the deterministic calculations are assessed using the DQI matrix. After calculation of the aggregated DQI scores, probability distributions for the parameters are determined using the transformation matrix (Table 3-3), and used as inputs for the MCS to carry out an influence analysis.

3.6.2.5 Categorization of Parameters

The degree of parameter uncertainty is obtained in the data quality assessment process. Parameters are consequently classified into groups of four with DQI scores belonging to the intervals of (1, 2), (2, 3), (3, 4) and (4, 5) respectively. The group containing parameters with DQI scores within the interval of (1, 2) and (2, 3) show the highest uncertainty, and the group with parameters scored within the interval of (3, 4) and (4, 5) represent the highest certainty. The influence of the input parameters on the results is determined via correlation analysis as given in Equation 3.7 (Wang and Shen, 2013).

$$r_{p,q} = 1 - \left[\frac{6}{(N^3 - N)}\right] \sum_{i=1}^{N} [rank(p_i) - rank(q_i)]^2 \tag{3.7}$$

Where rank (p_i) and rank (q_i) are the ranks of p_i and q_i among the N tuple data points.

The contribution of a single uncertain input parameter to the result of an impact category is calculated according to Equation 3.8 (Wang and Shen, 2013).

$$IA_{p,q} = r_{p,q}^2 \left[\sum_{p} r_{p,q}^2\right]^{-1} \times 100\% \tag{3.8}$$

Where $IA_{p,q}$ is the influence of input parameter p to output q; $r_{p,q}$ is the rank-order correlation factor between input p and the output q. $r_{p,q}$.

3.6.2.6 Detailed Estimation of Probability Distributions for Parameters

The statistical method is applied to the process of probability distributions fitting for the critical parameters identified. Kolmogorov-Smirnov goodness of fit test (K-S test) is used to fit data samples due to its sensitivity to variations in distribution types in terms of shape and scale parameters, and its intrinsic exactness compared to other goodness of fit tests e.g. Chi-square test and Anderson-Darling (A-D) test. The statistic for the K-S test is defined as:

$$D = \max_{1 \le i \le N} \left[F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i) \right] \tag{3.9}$$

Where F is the theoretical cumulative distribution of the distribution that is being tested, and N means N ordered data points Y_1, Y_2, …, Y_N.

For the non-critical parameters of lower uncertainty and influence, their probability distributions are estimated using the transformation matrix and the DQI scores, making the HDS approach more economical and efficient compared to the statistical method.

3.6.2.7 Final MCS calculation

The stochastic results are calculated by MCS algorithm, according to the input and output relationships, using the intricately estimated probability distributions for the parameters' as the inputs. Figure 3-3 shows the procedure for the HDS approach.

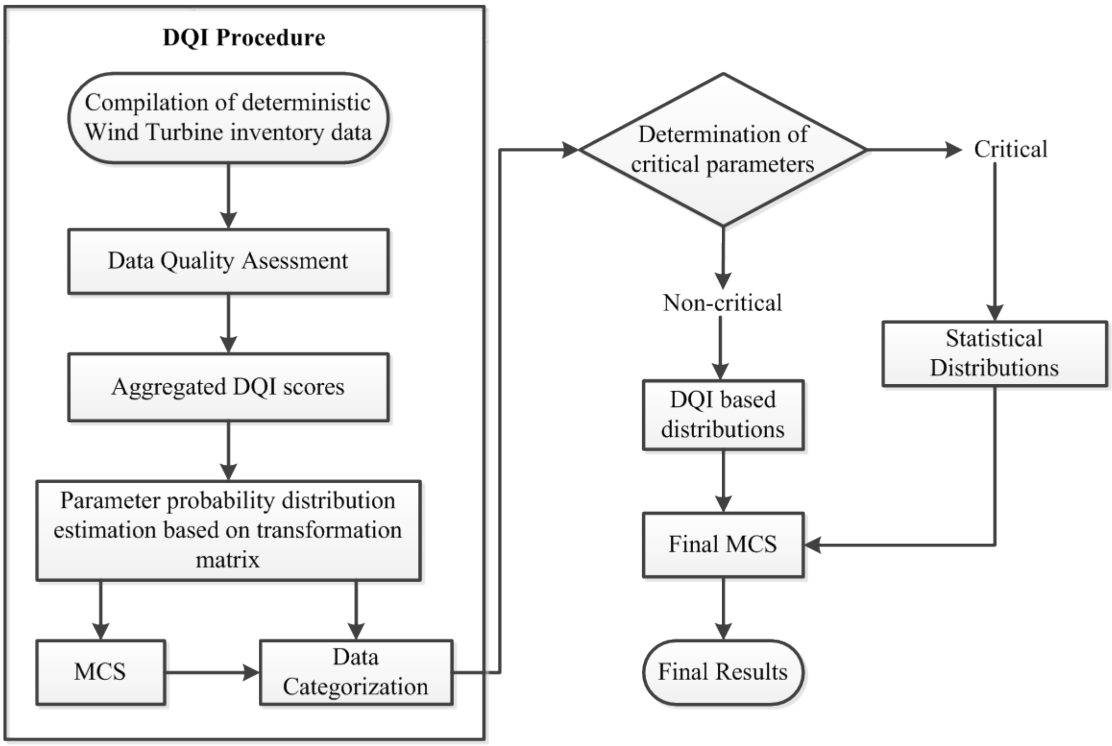


Figure 3-3. Procedure of HDS approach (adapted from Wang and Shen, 2013)

3.6.2.8 Validation

To validate the HDS approach, comparisons are made between the pure DQI, statistical and HDS methods. The measurements Mean Magnitude of Relative Error (MRE) (Eq. (3.10)) and Coefficient of Variation (CV) (Eq. (3.11)) are used to measure the differences in the results of the pure DQI and HDS. CV is an indicator that shows the degree of uncertainty and measures the spread of a probability distribution. A large CV value indicates a wide distribution spread. The data requirements are also used to compare the HDS with the statistical method, as large enough sample size needs to be satisfied during parameter distribution estimation. The least number of data points necessary for estimating parameter distributions in each method is calculated (Eq. (3.12)) and compared.

$$MRE = \frac{(M_{HDS} - M_{DQI})}{M_{HDS}} \times 100\% \tag{3.10}$$

Where M_{DQI} is the mean of the DQI results and M_{HDS} is the mean of the HDS results

$$CV = \frac{SD}{M} \tag{3.11}$$

Where M is the mean and SD is the standard deviation

$$N_M = N_{MD} \times N_P \tag{3.12}$$

Where N_M is the least number of data points required; N_{MD} is the least number of required data points for individual parameter distribution estimation; N_P is the number of parameters involved.

3.6.3 Economic Assessment

To assess the economic viability of a wind farm, the two important variables are the Operational Expenditure (OPEX), which is the sum of the operating costs of the farm during its life, and the Capital Expenditure (CAPEX), which is the initial investment (Leonardo Energy, 2013). These variables encompass the total costs associated with the wind farm during its lifetime, a term that is usually referred to as Life Cycle Cost (LCC). To decide whether or not to invest in a wind project, an estimation of the profitability or economic value of the project is essential, which is usually calculated with a financial model. According to Leonardo Energy (2013), the process of economic analysis can be summarized in three steps:

- First, forecast all the revenues and costs associated with the project during its lifetime and then convert them to cash flows.
- Next, different probable scenarios are set and the financial indicators calculated to determine profitability.
- Then, the results are analysed from the perspective of the different holders of capital.

Lastly, in relation to the indicators used to assess the economics of wind projects, Leonardo Energy (2013) gives the metrics that are most often used as:

- Net Present Value (NPV):
  - A positive NPV indicates that the project is profitable.
  - When selecting between different projects, that with the highest NPV should be embarked upon.
- Levelized Cost Of Energy (LCOE):
  - This metric is generally used to compare between different sources of generation.
  - The lower the LCOE, the greater the return for the investor.

- Payback period:
  - A project is more attractive if the payback period is lower than a particular desired term.
- Internal Rate of Return (IRR):
  - An IRR higher than the cost of capital indicates that a project is profitable.
  - When selecting between different projects, the one with the highest IRR is not necessarily the most attractive; if this is the case, the NPV rule should be followed.

To determine profitability, the financial indicator payback period, or the time required to pay back the investment, is used in this work to select the most advantageous wind turbine design variation. The choice of this indicator is as a result of it being one of the most requested measures of a renewable system's economic feasibility (Rashford et al., 2013). Leonardo Energy (2013) gives a brief explanation of payback period as follows:

3.6.3.1 Payback Period

As opposed to the other metrics above, the payback period only gives an indication of the liquidity of the project and does not address profitability. It is quite easy to calculate and intuitive for investors' intent on knowing the time required recuperating the initial investment. The payback period calculation generally compares the investment cost with the undiscounted cash flows generated by the project, with the purpose of providing an estimate of the length of time necessary to recover the investment. There is no consideration of the time value of money with this relatively simple calculation.

Rashford et al. (2013) gives the simple payback formula for a renewable system as:

$$Payback\ (years) = \frac{Capital\ Investment\ (\$)}{Annual\ Production\ \left(\frac{kwh}{year}\right) \times Income\left(\frac{\$}{kwh}\right) - O\&M\ (\frac{\$}{year})} \qquad (3.13)$$

Where,

Capital Investment = Total price paid for renewable energy installation

Annual Production = Amount of energy produced per annum (kilowatt-hours per year for electricity generating systems)

Income = Price paid for energy from utility (i.e., market price)

O&M = Operations and maintenance, including annual operating expenses

Revenue = Annual production × Income

The design variation with the shortest payback period is assumed to be the most advantageous. It is however noted in Rashford et al. (2013) that the simplicity of the payback calculation has limitations as it ignores several critical investment characteristics, including: alternative investment options, the time value of money, variable rate electricity pricing, energy price escalation, and what happens after payback.

3.6.3.2 Wind Farm Cost Model

The NREL study by Fingersh et al. (2006) investigated the costs of wind turbines using simple scaling relationships to estimate the cost of wind turbine subsystems and components for different configurations and sizes of components. The mass and cost formulas in the model are a direct function of tower height, machine rating, rotor diameter, or a combination of these factors. The overall cost model created to estimate the cost of the wind farm in this study includes 13 separate sub-models which estimate the costs of individual system components. These sub-models include tower, blades, generator, nacelle, grid connection, foundation, and other miscellaneous costs (i.e. transportation cost, land lease costs, etc). These models have as their primary input the hub height above the foundation in metre, annual energy production (AEP) in kWh, rotor radius in metre, and the generator rating in Kilowatts. Each sub-model is configured such that it receives an input, performs a set of procedures to calculate its component specific cost, and then adds up this component cost to the cost of the other sub-models to generate a total cost for the wind farm.

3.6.3.3 Capital Expenditure (CAPEX)

Capital Expenditure includes the costs of turbine manufacture, roads and civil works, transportation of turbines to site, and assembly and installation. The formulas used to estimate each of these components are given in the equations summarized below where R is given as the machine rating, h is the hub height, D is the rotor diameter, A is the rotor swept area, r is the rotor radius, BCE is the blade material cost escalator and $GDPE$ is the labour cost escalator. For the baseline turbine, the labour cost escalator was assumed to be the 2014 U.K. inflation rate of 1.64% (EU Inflation rates, 2015) while the blade material cost escalator was assumed to be 60% (Tegen et al., 2010). As TIO's 1 – 4 are concept designs, both the blade material cost escalator and labour cost escalator should remain as constants hence a value of one was chosen. It should be noted that the outputs of all the formulas are in American dollars (USD). Fingersh et al. (2006) gives the formulas as follows:

Blades

$$Baseline\ Cost = \frac{[(0.4019 \times r^3 - 955.24) \times BCE + 2.7445 \times r^{2.5025} GDPE]}{(1 - 0.28)} /blade \quad (3.14)$$

$$Advanced\ Cost = \frac{[(0.4019 \times r^3 - 21051) \times BCE + 2.7445 \times r^{2.5025} GDPE]}{(1 - 0.28)} /blade \quad (3.15)$$

In the equations above, the blade material cost is escalated with the composite escalator depending on technology, and the labour cost is escalated with the GDP.

Tower

$$Total\ Cost = mass \times 1.50 \quad (3.16)$$

Generator

$$Direct\ Drive\ Generator\ Cost = R \times 219.33 \quad (3.17)$$

$$Single\ Stage\ Permanent\ Magnet\ Generator\ Cost = R \times 54.73 \quad (3.18)$$

Nacelle

$$Cost = 11.537R + 3849.7 \quad (3.19)$$

Grid Connection

$$Electrical\ connection\ cost = 3.49 \times 10^{-6} R^3 - 0.0221 R^2 + 109.7R \quad (3.20)$$

$$Controls\ equipment\ cost = \$35{,}000$$

$$Total\ cost\ of\ grid\ connection = Electrical\ connection\ cost + Controls\ equipment\ cost \quad (3.21)$$

Foundations

$$Foundation\ cost = 303.24 \times (h \times A)^{0.4037} \quad (3.22)$$

Roads and Civil Works

$$Roads\ and\ civil\ works\ cost = 2.17 \times 10^{-6} R^3 - 0.0145 R^2 + 69.54 R \qquad (3.23)$$

Transportation

$$Transportation\ cost = 1.581 \times 10^{-5} R^3 - 0.0375 R^2 + 54.7 R \qquad (3.24)$$

Assembly and Installation

$$Cost\ of\ assembly\ and\ installation = 1.965 \times (h \times D)^{1.1736} \qquad (3.25)$$

3.6.3.4 Operational Expenditure (OPEX)

Operational Expenditure includes the cost of operation and maintenance, component replacement and land lease. The formulas used in the estimation of these costs are given below according to Fingersh et al. (2006).

$$Annual\ replacement\ cost = 10.7 \times R \qquad (3.26)$$

$$Operation\ and\ maintenence\ costs = 0.007 \times AEP \qquad (3.27)$$

$$Land\ lease\ costs = 0.00108 \times AEP \qquad (3.28)$$

3.6.3.5 Income

The income from a wind farm is made up of the Renewable Levy Exemption Certificates, Feed-in Tariff and Export value for each unit of energy produced (RenewablesFirst, 2015). The Feed-in Tariff is the largest component and is paid on electricity produced. The Feed-in Tariff is more generous for smaller wind farms to enable smaller investments and projects to be economically feasible. The current rates are shown in Table 3-4 (RenewablesFirst, 2015).

Table 3-4. Feed-in Tariff for wind energy

Wind Turbine Maximum Power Output	Feed-in Tariff (p/kWh)
15 kW to 100 kW	17.32
100 kW to 500 kW	14.43
500 kW to 1.5 MW	7.83
1.5 MW to 5 MW	3.32

The export value is the price of electricity sold to the grid which is negotiable and tends to favour large wind farms. There is a guaranteed minimum export value of 4.5p/kWh under the Feed-in Tariff used in this study. The Renewable Levy Exemption Certificate (LEC) is the final income component. It is issued by the Office of Gas and Electricity Markets (OFGEM) to generators of renewable energy and is sold on with the electricity to claim exemption from the Climate Change Levy (CCL) (HM Revenue & Customs, 2015). The LECs are worth 0.507p/kWh but are subject to a 90% administrative fee when sold so the net income they produce is 0.456 p/kWh (Renewables First, 2015). These components were summed for each wind turbine size category of the Feed-in Tariff. The income for each kWh of energy transmitted is shown in Table 3-5.

Table 3-5. Income per kWh of electricity transmitted

Wind Turbine Maximum Power Output	**Income (p/kWh)**
15 kW to 100 kW	22.276
100 kW to 500 kW	19.386
500 kW to 1.5 MW	12.786
1.5 MW to 5 MW	8.276

3.6.3.6 Currency Conversion

The income is calculated in Great British Pounds (GBP) using income factors only applicable to British wind farms but the wind farm costs are calculated in USD using an American cost model. To standardize the calculations, all values in USD were converted to GBP. The conversion rate is set at 1 USD to 0.67 GBP (Oanda, 2015).

3.7 Chapter Conclusion

The integrated methodology used for the sustainability assessment of the baseline turbine and potential TIOs is described in this chapter. The methodology encompasses identification of sustainability indicators and issues, scenario definition (baseline case and potential TIOs), data collection, data uncertainty propagation, environmental and economic assessments. It draws on the lack of work by other authors (as discussed in the literature review) and as a result, arguably addresses gaps in the body of knowledge. By adopting this approach, the methodology ensures that the different wind turbine design options can be considered on an equal basis, as well as allowing for the identification of factors that may act as key points for improvement.

Chapter 4 Background Theory of Wind Turbine Technology

Wind energy systems and its related processes present unique challenges though generally considered not as complex as those of other energy systems. As wind by its nature cannot be controlled, it is extremely important that all initial research is undertaken with as much detail as possible. In this chapter, the main concepts governing wind farm design are presented and an introduction to the guiding principles of wind farm energy yield estimation is provided.

4.1 Estimating Wind Farm Energy Yield

Calculation of the potential energy yield of a wind farm requires estimation of the energy that can be captured from the wind. Patel (2005) gives thermodynamic equations which can be used to describe energy in the air. The kinetic energy of a mass of air 'm', moving with a speed 'V' is given by the equation 4.1.

$$E_k = \frac{1}{2} m V^2 \tag{4.1}$$

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

$$Power = \frac{1}{2} \dot{m} V^2 = \frac{1}{2} (\rho A V) V^2 \tag{4.2}$$

Rewritten as

$$Power = \frac{1}{2} \rho A V^3 \tag{4.3}$$

Where,

V = velocity of the air, m/s
A = swept area of the blades, m^2
ρ = density of air, kg/ m^3
ṁ = mass flow rate
P = power in the moving air

The energy that can be extracted from the wind is however restricted as the wind turbine cannot extract all the upstream power in the wind. Some power is instead left in the wind downstream of the blades, implying that the speed of the air flow reduces. The actual power extracted by wind turbine blades is the difference between the upstream and downstream powers of the air flow.

$$Power = \frac{1}{2}\dot{m}(V_U^2 - V_D^2) \quad (4.4)$$

Where,

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

The average wind speed passing through the blades determines the mass flow rate of air through the blades.

$$\dot{m} = \rho A \frac{(V_U^2 + V_D^2)}{2} \quad (4.5)$$

Combining equations 4.4 into 4.5 gives:

$$Power = \frac{1}{2}\rho A V^3 C_p \quad (4.6)$$

Where,

$$C_p = \frac{\left(1 + \frac{V_D}{V_U}\right)\left[1 - \left(\frac{V_D}{V_U}^2\right)\right]}{2} \quad (4.7)$$

C_p expresses the fraction of upstream power that can be extracted from the wind and is known as power coefficient, or rotor efficiency. The C_p is restricted to a value of 0.593, which is known as Betz limit, hence only about 60% of the energy in wind can be converted into mechanical power (Hau, 2003). The Betz limit thus provides the maximum theoretical power that can be extracted from the wind, given conditions at the site. It is noted in Gasch and Twele (2011) that some modern wind turbines achieve C_p values of up to 0.5.

It can be seen from equation 4.6 that the power which is extractable from the wind increases with the third power of the wind velocity. Knowledge of certain physical laws and parameters are of importance if wind energy is to be exploited. While the turbulence is significant with regard to the control function and structural strength of a wind turbine, the long-term characteristics of the wind are relevant with regard to the energy yield. These long-term wind characteristics can be determined using statistical surveys over several years (Gasch and Twele, 2011). Power curve information of the wind turbines to be installed at each site is also required, and as such, wind farms are modelled on a case-by-case basis. These data are then used for determining the energy yield of a wind farm. Burton et al. (2001) states that knowing the power curve of a wind turbine P(V), the mean power production can be estimated using the probability density function of the wind speed at hub height f(V), which is typically expressed as a Weibull distribution (see Equation 4.8):

$$E = T \int P(V) f(V) dV \tag{4.8}$$

Where,

T = time period
f(V) = probability density function of the wind speed
P(V) = power curve of the wind turbine

The power curve is divided into a sufficient number of linear sections, typically for 0.5 m/s steps. The power output is calculated by summing up the produced energy for each wind speed bin. For an accurate description of the energy yield potential of a site, long term observations obtained directly at the site are essential. For most sites however, wind measurements rarely exist for an adequately long period. A description of some methods that can be employed to estimate the wind characteristics of a site is given below.

4.1.1 Measure-Correlate-Predict Method

This purely statistical approach, as explained in Gasch and Twele (2011), is based on the assumption that there is a linear relationship between simultaneous measurements at the reference site and the planning site. For example, using the hourly mean wind speed values *v*Ri at the reference site as x-coordinate and the simultaneous one *v*Pi from the planning site as y-coordinate, these values may be drawn in a Cartesian coordinate system. A regression line is then allowed to be drawn through the points under the assumption of a linear relation. The gradient of the line is a measure for the relation of wind speed at the reference site *v*R to the wind speed of the planning site *v*P. Calculating the correlation between the measuring data from planning site and reference site allows for statistical estimation of the relation between the wind regimes at the sites considered using the correlation coefficient R^2. It gives the linear correlation between the concurrently recorded data along with the variance. From the standard deviations and averages obtained, it is possible to determine the Weibull distribution function. If the correlation is adequately high i.e. $R^2 > 0.70$, the factors of the wind speed distribution at the reference site can be transferred to the planning site. A disadvantage of this approach is that the wind speed calculated is only valid for the individual measuring height at the position of the measuring mast exactly. A transformation of the long-term corrected wind regime to other points than the one measured is only likely using physical models which consider local site condition effects on the flow.

4.1.2 Wind Atlas

The wind atlas has become one of the most significant tools in recent years for determining sites for wind farms and predicting expected energy yield (Burton et al., 2001). Wind studies in European countries are produced almost exclusively with this approach if they cannot be based on evaluating measurements at the reference site. According to Hau (2003), the European Wind atlas consists of two parts: the first describing wind conditions in Europe and the second containing a mathematical approach by means of which the energy yield and wind conditions of a wind farm can be predicted for a particular site using these data.

The first part is based on measurement data available for a relatively long period (over at least 10 years) from about 220 measuring stations (Hau, 2003). These measurement data, generally measured at the standard height of 10 m, supply the raw data of the atlas. The measurement data includes measuring height, information on environmental roughness in directional sectors, local coordinates of the measuring station and frequencies of wind direction and wind speed specified in the sectors. The database also contains the annual and diurnal variation in wind speed. The wind atlas provides detailed information on how the measuring stations can be classified in accordance with the criteria of obstacles, orography and surface roughness. For this reason, the landscape is divided into four surface roughness classes and five different landscape types. The roughness length z_o is determined from the roughness elements (i.e. houses, large trees etc.). The corrected regional wind data is then calculated from the actual measurement data of the stations using correction factors derived from the roughness elements.

The second part of the wind atlas contains descriptions on how wind data for a potential wind farm site can be determined from the regional data (Hau, 2003). In this approach, the calculation of regional data using the local data from the measuring stations is reversed and the same mathematical and physical models are used. It is handled in such a way that an appropriate station situated within the surrounding area of the site is selected from regional wind data after which the site is classified in accordance with the criteria of surface roughness, shading by obstacles and orography. On this basis, Weibull parameters are calculated for at the heights of interest for the site.

In the United Kingdom, the NOABL wind speed database contains estimates of the annual mean wind speeds all over the country and is the result of an air flow model that estimates the effect of landscape on wind speed. This model is however simplified and there is no allowance for the effect of local winds such as mountain/valley breezes or sea breezes (Burton et al., 2001). The program provides data (based on coordinates) for a given grid reference and the surrounding areas, at three different heights (10 m, 25 m and 45 m above ground level) in 1 km boxes. It makes no allowance for local surface roughness (i.e. trees, crops, or buildings) which may have a significant effect on the wind speed.

4.2 Wind Speeds at Hub Height

Wind speed, and consequently power, changes with height above the ground. Wind moving across the surface of the earth encounters friction, as mentioned previously, caused by turbulent flow around and over obstructions in its path. Increase in height above the surface results in decreases in effects due to friction until unobstructed air flow is restored. Therefore, wind speed increases as friction and turbulence decreases. As a result of this, wind turbines are mounted on towers in order to allow them to intercept these faster air flows. Measurement masts are seldom of the same height as wind turbine towers hence, it is necessary to look for ways to extrapolate the wind speeds calculated at lower heights to the turbine hub height. According to Gipe (1991), the power law method is the easiest way to calculate the increase in wind speed with height. The power law equation is empirically derived from actual measurements. The power law wind shear exponent is illustrated in the following equation:

$$\frac{\bar{U}(z_1)}{\bar{U}(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha} \tag{4.9}$$

Where,

z = height above ground level
$\bar{U}$ = mean wind speed
α = power law wind shear exponent

The power law wind shear exponent is dependent on the height interval over which the equation is applied and varies with the type of terrain (Burton et al., 2001).

Another method using logarithmic extrapolation is common in Europe (Gipe, 1991). Logarithmic extrapolation is derived mathematically from a theoretical understanding of the way wind moves across the earth's surface. Wind speed variation with height can be demonstrated using the Prandtl logarithmic law model, where the logarithm of the measurement height is plotted against the recorded wind speed. The equation below defines the Prandtl logarithmic law model:

$$\bar{U}(z) = \left(\frac{u}{k}\right).ln\left(\frac{z}{z_o}\right) \quad (4.10)$$

Where,

z_o = the roughness length
k = von Karman constant
u = friction velocity
$\bar{U}(z)$ = mean wind speed at height z above ground level

Assuming neutral atmospheric conditions, the equation above is simplified to:

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

Where,

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

From the expressions above it can be seen that the roughness length z_o, affects the wind speed calculation at given heights. The roughness length is a parameter used to represent the roughness of the terrain over which airflow passes and is defined as the height upon which the mean wind speed is zero. Table 4.1, taken from the Danish Wind Industry Association, summarizes a range of roughness lengths defined for typical terrain types.

Table 4-1. Roughness classes for different landscapes

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

4.3 Air Density

Manufacturers characteristically develop power curves for application at sea level (non-site specific conditions) with a standard air density of 1.225 kg/m^3. As air density differs with meteorological conditions and site elevation, it is necessary to apply corrections to the expected power output from the power curve for differences in air density. Air density can be calculated for each hourly interval of the average annual wind speed using the ideal gas law (Gipe, 2004):

$$\rho = \frac{M.P}{1000.R.T} = \frac{M.P}{8.314T} \tag{4.12}$$

Where,

R is the universal gas constant $= 0.008314 \ \frac{\mathrm{m^3.KPa}}{\mathrm{mol.K}}$

T = Temperature (K)
P = atmospheric pressure (kPa)
M = molecular weight of air (g/mol)
ρ = air density (kg/m^3)

Equation 4.12 assumes air is a perfect gas with a molecular weight of 28.964 g/mol. De Nevers (2010) cites a correction to the calculation of the molecular weight of air in order to account for the effects of water content in air on air density.

$$M_{avg} = 28.964 - 0.253\,(RH) \qquad (4.13)$$

Where,

RH = relative humidity, expressed as a decimal
M_{avg} = average molecular weight of air (g/mol)

When these equations are combined, the air density can be calculated as follows:

$$\rho = \frac{[28.964 - 0.253(RH)]P}{8.314T} \qquad (4.14)$$

Equation 4.14 accounts for the majority of the difference between the air densities at sea level and the wind farm location. Thus, the power output extracted from the power curve is proportionately scaled to the calculated hourly air density at the wind farm location by applying Equation 4.15.

$$P_{Adj} = \frac{P_T.\rho}{\rho_{Std}} \qquad (4.15)$$

Where,

ρ_{Std} = air density at standard conditions (1.225 kg/m^3)
ρ = air density (kg/m^3), calculated for each hourly observation
P_T = Power Output (kW), obtained from power curve
P_{Adj} = Expected hourly power output (kW), adjusted for air density

4.4 Wind Farm Energy Loss Factors

After wind farm design tools have been used to calculate the output of a wind farm, it is essential to estimate a range of possible sources of energy loss. According to the European Wind Energy Association (2012), wind farms have six main sources of energy loss, each of which could be subdivided into more detail. The main loss factors used to predict net energy output for a wind farm are described below.

Curtailments

All or some of the wind turbines in a wind farm may possibly need to be shut down to alleviate issues associated with certain planning conditions, turbine loading or export to the grid.

Environmental

Overtime the surface of the blade may deteriorate or in certain conditions, dirt can form on the blades. Ice can also build up on a wind turbine. These influences can affect a wind farms' energy production. Extremes of weather can also affect the energy production of a wind farm.

Turbine Performance

In an energy production calculation, a manufacturer supplied power curve is used in the analysis. Losses need to be assumed however for the inconsistency between actual site conditions, power curve measurement conditions and losses due to high wind shutdown.

Electrical Efficiency

Electrical losses will be experienced between the low voltage terminals of each of the wind turbines and the point of connection of the wind farm, which is usually located within a wind farm switching station.

Availability

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

Wake Effect

When wind turbines extract energy from the wind, there is a wake downstream from the wind turbine where wind speed is reduced. As the flow proceeds downstream, there is a scattering of the wake and the wind speed improves towards free stream conditions. The wake effect is the combined influence on the energy production of the wind farm as a result of changes in wind speed due to the influence of the turbines on each other.

4.5 Chapter Conclusion

The guiding principles of wind energy estimation and the main concepts governing wind farm design are described in this chapter. The chapter discusses the tools used for estimation of wind farm energy yield, methods for estimating wind characteristics of a site, and loss factors used to predict net energy output for a wind farm. It draws on the body of knowledge in wind turbine technology and as a result addresses the unique challenges associated with wind energy systems and its related processes. This chapter hence is the basis for the life cycle modelling of the wind farm using the different wind turbine design options.

Chapter 5 Lifecycle Modelling of Wind Farm

This chapter outlines the basic theory behind wind power utilization and illustrates how the wind farm model used for the comparison was created. A systematic description of all inputs provided for each model is carried out, specifying all the assumptions made in order to enable the creation of an accurate onshore wind farm lifecycle model. The wind farm model is presented to highlight the key differences in modelling requirements. As such, the wind farm is modelled using the different wind turbine design variations.

5.1 Wind Farm Model

For the purpose of this study, the wind farm created is based on near future and current trends in wind farm construction projects. In order to build and properly size the model, existing conditions from a real wind farm was carefully modelled and data at the real site was used as a reference. As the intention of this investigation is to carry out wind farm life cycle modelling that meets future and current development expectations, the establishment of areas for projected future and current wind farm development is the first step to creating a model. According to information supplied by the British Wind Energy Association (BWEA, 2015) which chronicles wind projects that have building permission and accounts for projects that are under construction, Wales has the least of projected and current wind farm development. This is therefore an indication that Wales is the least representative area in the British Isles for wind power development. It is also observed that most of the developments in Wales are concentrated in the south of the country, bordering the Celtic Sea.

With the establishment of a geographical area of interest, the next step is choosing a project that represents the nature of prospective wind power developments. After meticulous consideration of wind farms currently in their construction phase, the Pen y Cymoedd onshore wind farm, which was given planning consent in May 2012, was used as the reference wind farm for this study. The wind farm is situated within the Coed Morgannwg Strategic Search Area, South Glamorgan in Wales, and is projected to have a maximum installed capacity of 299 MW comprising of 76 wind turbines. The site is approximately 46.8 km^2 (as anticipated at the time of consent) (Nuon, 2009). The actual capacity of the wind farm will depend on the precise turbine manufacturer selected for the installation. Each turbine will not be less than 2 MW hence the total minimum capacity will be 168 MW.

In the Pen y Cymoedd wind farm Non-Technical Summary (Nuon, 2009), the proposed construction is set to include four anemometry masts, site tracks, borrow pits, underground on-site electricity cables and an underground grid connection route, an on-site 33/132 kilovolt (kV) substation which will house a switchgear and metering building, construction compounds and associated works/infrastructure. The maximum dimensions of the wind turbines are also set out at an overall base to tip height not exceeding 145 metres. The operational life time of the wind farm is expected to be 25 years after which the wind farm will be decommissioned and above ground structures removed.

The model created for this study includes most aspects of the life cycle of the wind farm covering construction, operation and decommissioning at the end of the operational lifetime. In this research, the turbines installed onsite have a 1.5 MW capacity rating. Thus, the installed capacity of the wind farm will be 114 MW which is less than the projected wind farm capacity but within the maximum installed capacity of 299 MW. Table 5-1 summarizes the characteristics of the model wind farm below:

Table 5-1. Wind farm characteristics

Location	**Pen y Cymoedd, South Wales**
Rated Output (MW)	114
Number of turbines	76
Turbine rated Output (MW)	1.5
Project Lifetime (years)	25

The wind regime at the site of the proposed wind farm has to be estimated in order to calculate the potential farm output. For this to be done, the requirements for providing accurate energy output estimates and an understanding of how wind power works is essential. The following sections present a systematic description of how the wind farm model was setup, as well as information on all the major assumptions.

5.2 Description of the Proposed Site

An assessment of the terrain surrounding the wind farm is an important aspect of any wind resource analysis. This is essential because surface roughness and elevation changes are important inputs into the wind flow modelling as well as an indication of the possible effect that the topography of the surrounding terrain will have on wind turbine performance. It was not possible to carry out analytical wind flow modelling for the assessment carried out in this study but terrain assessment still influenced wind speed variation with height estimation as will be seen in the following sections.

Information and map services provided by the British Wind Energy Association (BWEA, 2015) established the location of the wind farm to be approximately between the coordinates of 51° 42' 1"N and 3° 37' 27"W as shown in Figure 5-1. The location of the wind farm can be seen in the satellite image in Figure 5-2 (Google maps, 2014). From the image, it can be seen that extensive forestry characterizes the area surrounding the wind farm. The Celtic Sea is to the southwest of the site, which could also influence wind flow behaviour as it approaches the wind farm from those areas.

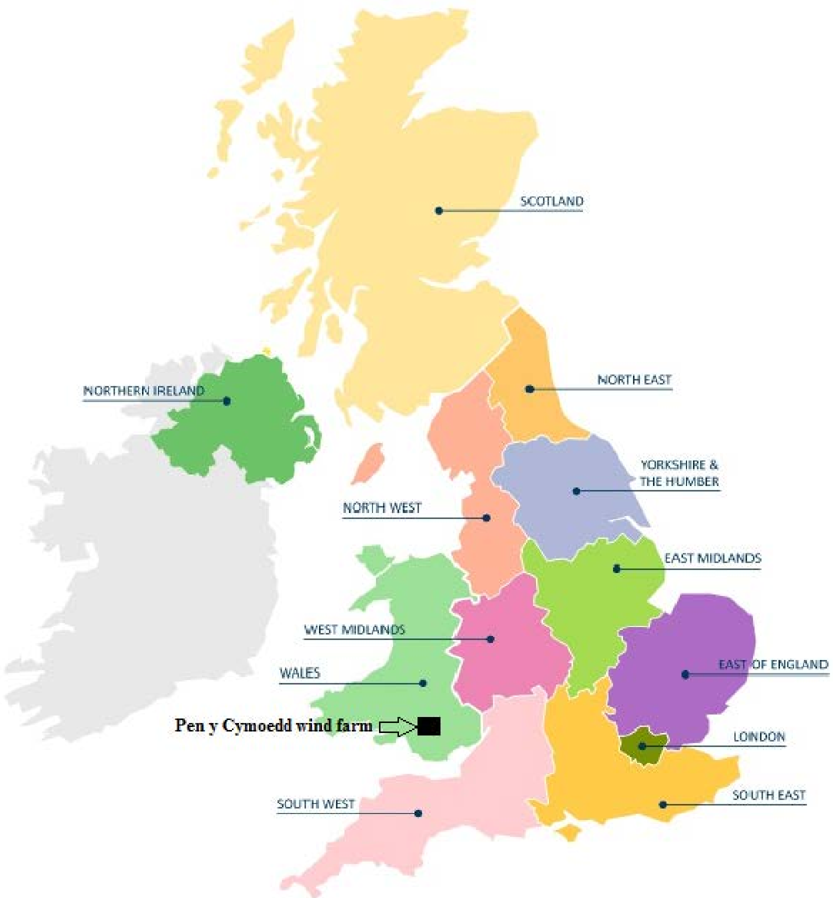


Figure 5-1. Location of Pen y Cymoedd wind farm in the U.K

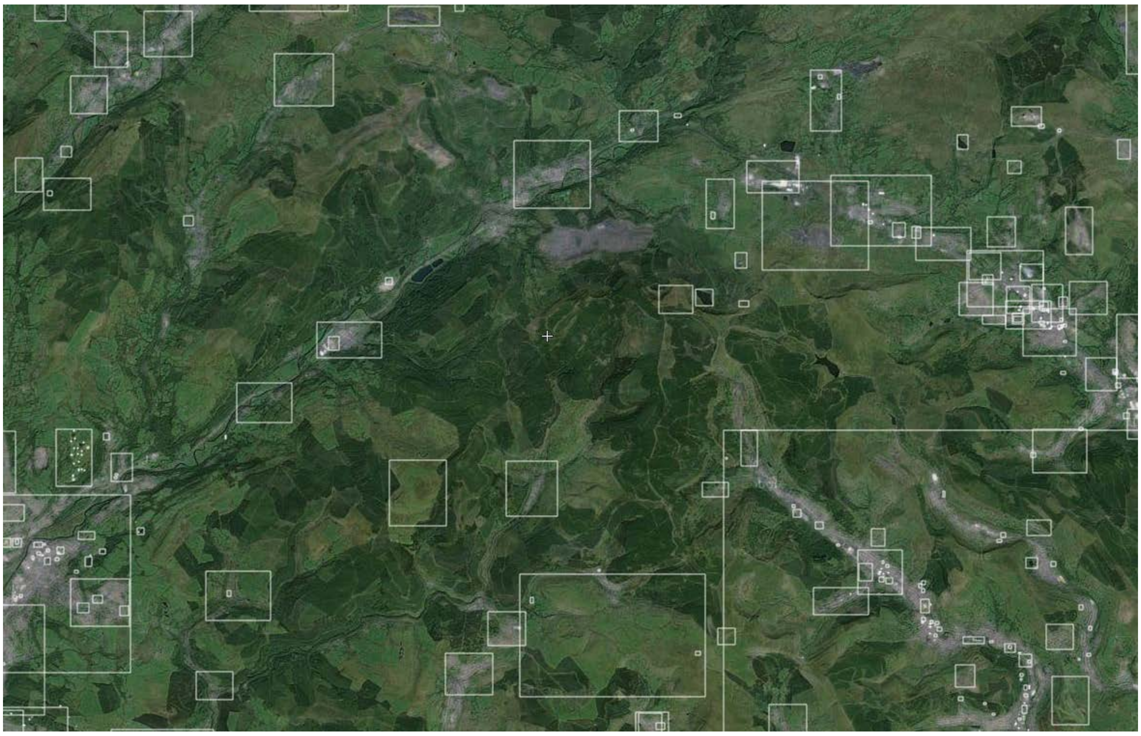


Figure 5-2. Surrounding terrain of Pen y Cymoedd wind farm

Low level vegetation in the form of tall grasses, shrubs, and bogs and fens was judged to constitute the terrain not immediately associated with forestry. Images of the wind farm site available in the public domain further assisted assessment of the terrain type as can be seen in Figure 5-3 (StayinWales, 2012; RE News, 2013).

Figure 5-3. Images of Pen y Cymoedd wind farm

5.3 Site Wind Resource

A description of the available wind resource at the proposed site is essential for wind electricity production assessment. For the Pen y Cymoedd wind farm case study, site specific publicly available information was not obtainable in literature sources to help estimate the wind resource. This resulted in a search for recorded data at neighbouring locations which could be modified to generate estimates for the location of the wind farm. In the UK, the meteorological office has a substantial collection of meteorological data for several locations across the country (known as the MIDAS Land Surface Observation Stations Data) through its network of sensors. No wind speed data was readily available for the exact location of the proposed wind farm but numerous meteorological stations that could provide information were identified. Three meteorological stations were found to be available after being filtered for distance (they were all located within 70 km of the site). The table below summarizes the stations found.

Table 5-2. Meteorological stations near the proposed wind farm

Met Station	**Altitude (m)**	**Distance (km)**	**Direction**
St Athan	49	31	East
Mumbles Head	43	43	Southwest
Sennybridge No 2	307	66	North

The MIDAS database meteorological data from the meteorological stations contained consistent hourly averages of wind direction and speed for the period 2005 to 2014 for all three stations. The MIDAS user guide (United Kingdom Meteorological Office, 2015) states that the standard exposure for all meteorological stations measurements is over level, open terrain at a 10 m height above the ground. The average mean wind speed at 10 m was established using this data and is shown below:

Table 5-3. Wind speeds at the meteorological stations

Met station	**Average Wind Speed (m/s)**
St Athan	9.4
Mumbles Head	13.3
Sennybridge No 2	6.8

To calculate the wind resource at the site, the method of assessment preferred would be to correlate any data recorded directly at the site with data from the chosen meteorological station. As the meteorological station will have recorded data for a considerably longer period than would be available at the site, the correlation would be based on the concurrent data period between the two locations. After this correlation is established, it is then used in the derivation of a long-term data set for the site by scaling the non-concurrent data by a factor estimated from the concurrent period. This scaled data set could then be used for the analysis. There was however no on-site data available making a standard correlation between the reference station and the site data an impossibility.

To get around this shortcoming, an approach for scaling wind speeds was conceived using the relative wind speeds of the meteorological station location and the site as calculated from a third information source. The NOABL wind speed database (Rensmart, 2015) is this third source of information. As previously stated in the last chapter, the NOABL database provides an indicative measure of the average annual wind speed at any U.K. location and could therefore be used here in the estimation of the relative wind speeds for the two locations. With this information, it is then possible to establish a measure of how windy the proposed wind farm site is compared to that at the meteorological station location.

Using the NOABL database wind speed predictions for the proposed wind farm site and the mast locations at 10 metres, an adjustment factor that would need to be applied to the actual site measured data so as to scale it to a predicted site wind speed was calculated. Table 5-4 below shows the calculated adjustment factor and the ensuing onsite wind speed based on each mast.

Table 5-4. Site wind speed predictions using reference station data

Station	**NOABL Mast Prediction (m/s)**	**NOABL Site Prediction (m/s)**	**Adjustment factor**	**Mast Wind Speed Measurement (m/s)**	**Predicted site wind speed (m/s)**
St Athan	5.6	6.8	1.21	9.4	11.4
Mumbles Head	6.2	6.8	1.1	13.3	14.6
Sennybridge No 2	6.4	6.8	1.06	6.8	7.17

The range of predicted site wind speeds shown above prompted a weighted average approach of the three values that would give the most durable solution. Thus, the inverse-squared distance method (Shepard, 1968), was used to weigh the above estimated site wind speeds using the following equation:

$$V_{site} = V_1 \times \frac{{D_1}/{D_T}}{L} + V_2 \times \frac{{D_2}/{D_T}}{L} + V_3 \times \frac{{D_3}/{D_T}}{L} \tag{5.1}$$

Where,

$$L = \frac{D_1}{D_T} + \frac{D_2}{D_T} + \frac{D_3}{D_T}$$

$$D_T = D_1 + D_2 + D_3$$

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

$$V_{1-3} = reference\ wind\ speeds$$

$D_{1,}$ D_2 *and* D_3 = values at the location coordinates of the data points

x_{site} and y_{site} = location coordinates of data points at the wind farm site

x_1 and y_1 = location coordinates of data points at the meteorological station

Using this approach a predicted site wind speed of 11.4 m/s at 10 metres was obtained.

A fundamental limitation of this methodology is the assumption that all the wind turbines experience the same wind regime i.e. the whole site experiences the same wind speeds. In cases where turbines are sited in difficult terrain however, this assumption is inherently flawed and can introduce significant errors in the energy output calculations. This limitation could be reduced to an extent using the wind flow modelling technique. For this study, the use of this technique was not possible due to the lack of suitable modelling capabilities. Figure 5-4 shows the location of the wind farm in relation to the meteorological stations.

Figure 5-4. Location of the meteorological stations and Pen y Cymoedd wind farm

5.4 Hub Height Wind Speed Calculation

The average annual wind speed, as stated in Section 5.3, was estimated from data recorded at 10 m above ground level. To calculate the energy production of the wind turbines however, an estimate of the hub height wind speed is required. To determine this value the Power Law (Equation 4.9) was utilized. The reason for this decision is because of the lack of accurate data necessary for employing the Log Law and also because the equations provided a conservative estimate of the wind speed at hub height. To use the Power Law equation to calculate the shear exponent α, an estimate of the all-directional average roughness value is necessary. This value is based on an empirical estimation method, using the site image extending 10 km around the wind farm in all directions (Troen and Petersen, 1989). The percentage terrain makeup is then established and weighted using the appropriate roughness classes.

Dividing the area surrounding the wind farm site into 8 segments (of 45 degrees each), the mix of grassland and woodland was estimated. 87.5% of the segments, from the northwest to the south, were estimated to be covered by a comfortable percentage of woodland (60%) and a lesser percentage of agricultural and grass land (40%). For the outstanding 12.5% of the surrounding area, primarily towards the southwest of the site, agricultural and grassland constitutes the larger percentage (90%) with woodland far smaller (10%). Based on the roughness classes described in Section 4-2, roughness values of 0.4 m and 0.03 m were assigned to the woodland and agricultural/grassland features respectively. Upon calculation of the estimates, they were multiplied with values using the roughness classes established in Section 4-2.

With the establishment of the all directional roughness value, the shear exponent is estimated using the equation provided in Gipe (2004):

$$\alpha = \frac{1}{ln\left(\frac{z}{z_o}\right)} \tag{5.2}$$

Where,

z = wind turbine hub height
z_o = estimated roughness value

From the equation above, it can be seen that the wind shear is mostly influenced by the terrain and roughness near the point of measurement. It is noted in Troen and Petersen (1989) that the wind flow at any location is affected by terrain many metres upwind of it. The shear exponent was consequently calculated to be 0.19 (for the baseline turbine, TIO 1 and TIO 3) and 0.17 (for TIO 2 and TIO 4) respectively. According to Gipe (2004), the shear exponent of flat terrain is around 0.14 thus, the value calculated for the location of the wind farm is reasonable. Substituting this shear exponent into the Power Law, the average wind speed at hub height for the baseline turbine, TIO 1 and TIO 3 was calculated to be approximately 16.3 m/s. Average hub height wind speed for TIO 2 and TIO 4 was calculated to be 16.9 m/s.

5.5 Wind Turbine Information

As previously indicated in Chapter 3, for this research the wind farm model is based on an Enercon E-66 1.5 MW turbine. The turbine's theoretical power output assumed for this study is lower than that of the turbine type actually chosen for the wind farm. The 1.5 MW turbine size is currently still in production by most large manufacturers (e.g. Suzlon, Vestas, Enercon, Nordex, General Electric, Fuhrlander) and continues to be used worldwide for projects. It is vital to point out that the size and choice of turbine type is dictated by site-specific as well as economic criteria. However short of a full analysis of the site, it is unfeasible to precisely decide on the design of the turbine. Thus, the Enercon E-66 turbine used in this study is assumed to be an acceptable choice for the site. It is however noted that a Siemens 3MW direct drive turbine was selected for the site in late 2013. A technical summary of the Enercon E-66 1.5 MW turbine is shown in Table 5-5 below (Papadopoulos, 2010).

Table 5-5. Technical characteristics of E-66 turbine

MODEL:	**ENERCON E-66**
Rated capacity:	1.5 MW
Rotor diameter:	70 m
Hub height:	65 m
Swept area:	3421 m^2
Converter concept:	gearless, variable speed, variable blade pitch
Rotor with pitch control	upwind rotor with active pitch control
Number of blades:	3
Rotor speed:	variable, 10 - 22 rpm
Tip speed:	35 – 76 m/s
Pitch control:	three synchronized blade pitch systems with emergency supply
Generator:	direct-driven ENERCON synchronous ring generator
Grid feeding:	ENERCON inverter
Braking system:	3 independent pitch control systems with emergency supply

5.6 Expected Energy Output of the Wind Farm

In order to calculate a wind turbine's annual energy output in a wind regime, the approach used was to merge the wind turbine power curve with the wind speed frequency distribution, hence calculating the energy output at each wind speed interval. The wind turbine energy output for a year is therefore the sum of these hourly energy outputs. The power curve used in this research is produced as a consensus power curve merging the different power curves of three 1.5 MW wind turbines: the Suzlon S.82, the Nordex S77 and the Fuhrlander FL 1500, as provided by a University of Puerto Rico study in 2012. Though the consensus power curve is clearly not specific to any machine, it was taken to represent the standard energy output of a 1.5 MW wind turbine.

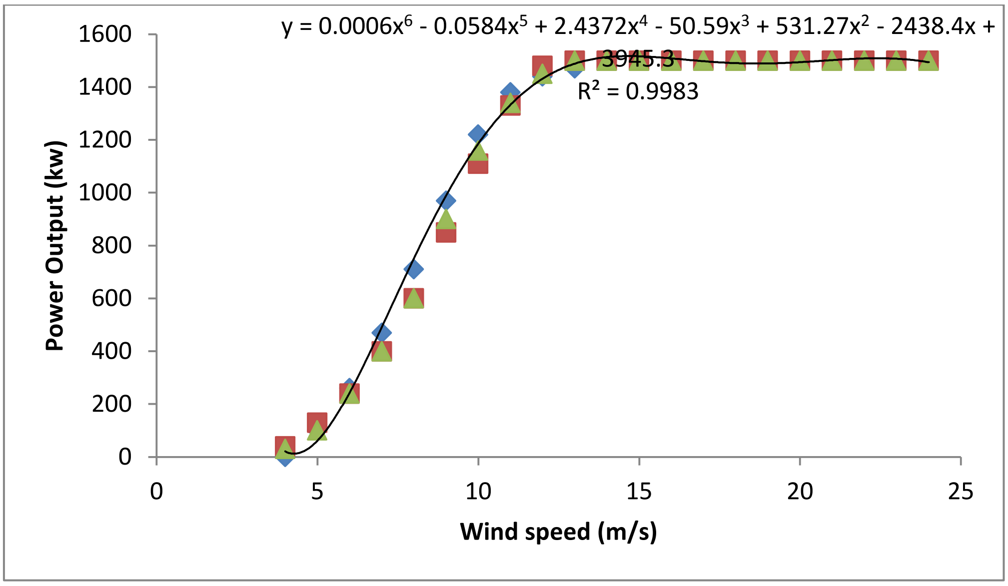


Figure 5-5. Consensus power curve for a standard 1.5 MW turbine

It can be seen from the figure above that between 4 m/s and 13 m/s, the power curve increases and then evens out at 1500 KW until the cut-out speed at 24 m/s. To convert the power curve to a format that is usable, it was approximated using the 6th order polynomial equation given below:

$$y = 0.0006x^6 - 0.0584x^5 + 2.4372x^4 - 50.59x^3 + 531.27x^2 - 2438.4x + 3945.3 \qquad (5.3)$$

To calculate the energy output of each wind turbine, the power curve is multiplied by the frequency distribution. The technique used is based on using the Weibull distribution and the predicted site mean wind speed. For the Weibull distribution, a shape factor (k) of 2 was chosen (a value that is consistent over northern Europe (Gipe 2004)), and the scale factor (C) was based on the equation C = average hub height wind speed / 0.9, as given in Patel (2005). The total energy produced by the wind farm is then estimated by aggregating the energy produced by all the turbines in the wind farm. Downward corrections then need to be made to account for the losses typical in the operation of wind farms.

5.6.1 Wind Farm Energy Loss Factors

In this study, six main sources of energy loss are considered; environmental, curtailments, turbine performance, electrical efficiency, wake effect and availability with each subdivided into more detailed loss factors as explained in Section 4.4. Table 5-6 summarizes the energy losses assumed for this project.

Table 5-6. Losses assumed for wind farm model (Gipe, 2004)

Production Losses	
Curtailments	
Wind sector management	N/A
Grid curtailment	N/A
Noise and visual	N/A
Environmental	
Performance degradation – non icing	N/A
Performance degradation – icing	1%
Icing shutdown	0.2%
Temperature shutdown	N/A
Site access	N/A
Tree growth (year 1 status assumed)	N/A
Turbine Performance	
High wind speed hysteresis	0.6%
Site specific power curve adjustment	N/A
Electrical efficiency	
Operational electrical efficiency	3%
Wind farm consumption	3%
Availability	
Turbine availability	2%
Balance of Plant availability	0.2%
Grid availability	N/A
Wake effect	
Wake effect internal	7%
Total	17%

The specific values used in the above table are based on assumptions given below:

(i) Curtailments

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

a) Wind sector management: Turbine loading is influenced by the wake effects from nearby turbines. For some wind farms with particularly close turbine spacing it may be necessary to shut down some turbines for certain wind conditions. This is referred to as wind sector management and will usually result in a reduction of the wind farms' energy production.

b) Grid curtailment: Within certain grid connection agreements it may be required to limit the output of the wind farm at certain times hence, resulting in a loss of energy production. This factor also includes the time taken for the wind farm to become fully operational following grid curtailment.

c) Visual, noise, and environmental curtailment: In certain jurisdictions there may be requirements to shut down turbines during specific meteorological conditions to meet defined shadow flicker criteria, noise emissions at nearby dwellings, or environmental conditions due to environmental requirements as regards bats or birds.

(ii) Environmental

Dirt and ice can form on the wind turbine blades in certain conditions or over time the surface of the blade may deteriorate. As described in the sections below, these influences can impact the energy production of a wind farm. The extremes of weather as well as tree growth and felling can also impact the energy production of a wind farm.

a) Performance degradation – non icing: The performance of wind turbines can be affected by blade degradation which includes the accumulation of dirt and other matter, as well as physical degradation due to prolonged operation which decrease the aerodynamic efficiency of the blades.

b) Performance degradation – icing: Small amounts of icing on the turbine blades can change the aerodynamic performance of the machine resulting in energy loss. The factor used in the modelling is based on the assumption made by Matthies and Aktiengesellschaft (1995).

c) Icing shutdown: As the accumulation of ice gets more severe wind turbines will shut down. Icing can also affect the wind vane and anemometer on the turbine nacelle which govern the operations of the turbine. A malfunction of these instruments can cause a shutdown of the turbine. The factor used in the modelling is again based on assumptions made by Matthies and Aktiengesellschaft (1995).

d) Temperature shutdown: Turbines are designed to operate over a specific temperature range. At certain sites, this range may be exceeded and during the period when the allowable temperature range is surpassed the turbine will be shut down.

e) Site access: Severe environmental conditions can influence access to more remote sites which can impact availability. An area prone to severe snow drifts in the winter is an example of this factor.
f) Felling/tree growth: For wind farm sites located close to or within forestry, the impact of how the trees may change over time and the effect this will have on site wind flow and consequently, the energy production of the wind farm must be considered. This was however deemed outside the scope of this effort.

(iii) Turbine Performance

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

a) High wind hysteresis: Most wind turbines will shut down when the wind speed exceeds a certain limit. Significant fatigue loading is caused during high wind speed shut down events. In order to prevent repeated start up and shut down of the turbine when winds near the shutdown threshold, hysteresis is usually introduced into the turbine control algorithm. The factor used in this study hence accounts for the interval in restarting the wind turbine after shutdown and is based on assumptions made by the European Wind Energy Association.
b) Site specific power curve adjustment: Power curves for wind turbines are usually based on power curve measurements made on simple terrain test sites. Certain wind farm sites may experience conditions of wind flow that differ from conditions seen at terrain test sites. Where it is considered that the parameters in some areas of a planned wind farm site considerably differ from those at the test station, the effect on energy production is estimated.

(iv) Electrical efficiency

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

a) Operational electrical efficiency: This factor defines the electrical losses experienced when the wind farm is operational and will manifest as a reduction in the energy measured by an export meter at the point of connection. The factor used is based on assumptions made by the European Wind Energy Association.

b) Wind farm consumption: This factor defines the electrical efficiency due to the electrical consumption of the non-operational wind farm as a result of consumption by electrical equipment and transformer no-load losses within the turbines and substation. The factor used here is based on assumptions made by Yes2wind (2015).

(v) Availability

Wind turbines, the electrical grid and the "balance of plant" infrastructure will not be available the whole time over the lifetime of a wind farm. Hence, estimates are included for likely availability levels for these factors averaged over the lifetime of the project.

a) Turbine availability: This factor defines the expected average turbine availability of the wind farm over its life time. It represents the factor which needs to be applied to the gross energy to account for the energy loss associated with the time the turbines are unavailable for electricity production. The factor assumed for the modelling is based on Papadopoulos (2010)'s estimate of the availability of the E-66 wind turbine.
b) Balance of Plant availability: This factor defines the expected availability of the on-site electrical infrastructure, turbine transformers and the substation infrastructure up to the point of connection to the grid of the wind farm. It represents the factor that needs to be applied to the gross energy in order to account for the energy loss related with the downtime of the balance of plant. The factor assumed here is taken from Matthies and Aktiengesellschaft (1995).
c) Grid availability: This factor defines the expected grid availability for the wind farm in mature operation. It also accounts for delays in the wind farm coming back to full operation following a grid outage. It represents the factor that needs to be applied to the gross energy to account for energy loss related with the downtime of the grid connection.

(vi) Wake effect

The wake effect is the aggregated influence on the energy production of a wind farm as a result of the wind speed changes caused by the impact of the turbines on each other. The factor used here has been assumed based on information in Nelson (2013).

Using the analytical wind data, the assumptions above and assuming 3000 actual load hours per year, the gross annual energy output of the baseline turbine, TIO 1 and TIO 3 was estimated to be 3.36 GWh/year. For TIO 2 and TIO 4, 3.4 GWh/year was estimated to be the gross annual energy output for both designs. After estimation of the annual energy output for the individual turbines, the value was multiplied by the number of turbines in the wind farm to generate the annual energy output of the wind farm. Corrections accounting for the losses due to criteria described in Table 5-6 (calculated to be 17%) was used to modify the estimate for annual output a final time. Based on these assumptions, the annual energy output of the modelled wind farm (using the baseline turbine, TIO 1 and TIO 3) was estimated to be 212 GWh/year yielding a capacity factor of 21%. Modelling the wind farm using TIO 2 and TIO 4, annual energy output was estimated to be 215 GWh/year with a capacity factor of 22%. These values are in line with predicted capacity factors for the U.K. as will be seen in the following section.

5.7 Capacity Factors in the U.K Wind Energy Sector

The capacity factor of a wind turbine in its particular location is another way of stating the annual energy output from a wind turbine. It is the ratio of the actual output of a wind energy development to the installed capacity (Oebels and Pacca, 2013). Capacity factor depends on many parameters, mostly the local wind resource, which in turn depends on the wind farm location. Thus, capacity factors vary significantly across countries and regions.

Examination of the evidence supplied by the UK's onshore wind energy operators to OFGEM provides an interesting insight. According to Jefferson (2012), the mean capacity factor achieved by onshore wind farms in England was 22.7% in 2007. Capacity factors also ranged from 35.09% (Haverigg 3 wind farm), to 24 wind farms attaining less than a 20% capacity factor (out of 81 operational farms throughout 2007). Of the latter, six wind farms attained a capacity factor below 10%. Performance was slightly higher in 2008, as it turned out to be a windier year, with wind farm capacity factors in Eastern England increasing to 26.2% in 2008 from 22.7% in 2007.

In a report published by Oswald and Ashraf-Ball (2007), a regional analysis of capacity factors was provided. Given the higher mean wind speeds prevalent in Scotland, it is not surprising that higher capacity factors have been recorded compared to England. The average capacity factor in 2006 for southern Scotland was estimated to be 27.6%. The study also highlights capacity factors for the year 2009 as ranging from 15.8% (Isle of Luig wind farm) up to 48.3% (Barradale Phase 2 wind farm). In 2010, an average capacity factor of 23.75% was estimated to be achieved in Scotland, indicating a less windy year compared to 2009.

In Jefferson (2012), Northern Ireland and Wales were noted to turn in lower capacity factors. The average capacity factor achieved in Wales in 2009 was 23.86% (covering the performance of 32 wind farms), and 18.75% in 2010 (with 38 wind farms covered). Three wind farms achieved capacity factors exceeding 30% in 2009 (Moelogen wind farm being the highest at 33.4%). In 2010, 22 wind farms attained capacity factors below 20%, nearly two-thirds of all wind farms in Wales. In Northern Ireland 32 wind farms were reviewed for 2009 and 43 wind farms for 2010. The average capacity factor achieved in 2009 was 24.1%, and 17.6% in 2010. The Owenreagh wind farm achieved the highest capacity factor in 2009 (38.2%), with five wind farms achieving more than 30% and nine wind farms achieving under 20%.

As can be seen from the studies above, capacity factors for wind farms in the U.K vary quite significantly depending on location. It is interesting to note that although wind farms in Northern Ireland and Wales generally had lower capacity factors compared to those in England and Scotland, the figures also suggest that annual variations in local wind resource are too significant to draw any type of conclusion as regards assumptions about the commercial and technical feasibility of wind farm projects.

5.8 Construction of the Wind Farm

In this section the energy and material inputs required for the construction of the wind farm model are dealt with. These inputs are based on information collected from databases as well as external sources as stated in Section 3.5. Each life cycle stage is split into different components while the assumptions and information sources are highlighted. The wind farm construction component consists of two inputs: the "materials" sub-assembly and the "processes" sub-assembly. The "materials" sub-assembly is a single input covering the different components of the wind turbine, while the "processes" sub-assembly covers the transportation and energy components required for construction of the wind farm. Both sub-assemblies are multiplied by a factor of 76, which is the number of wind turbines that make up the wind farm.

5.8.1 Data Source for the 1.5 MW Wind Turbine

As previously mentioned, the turbine model used in this research is an Enercon E-66 three-blade horizontal axis wind turbine. Although this turbine model is not completely representative of the most recent wind turbine designs, it was chosen for modelling the wind farm since it conformed to the acceptable wind turbine dimensions as stated in the Pen y Cymoedd wind farm Non-Technical Summary. Data for the turbine was taken from a PhD thesis (Papadopoulos, 2010). This source was used in this study to provide a comprehensive dataset for the E-66 turbine.

5.8.2 Construction of Wind Turbine

Modelling of the Enercon E-66 wind turbine was carried out by splitting it into the following components shown in Figure 5-5 below:

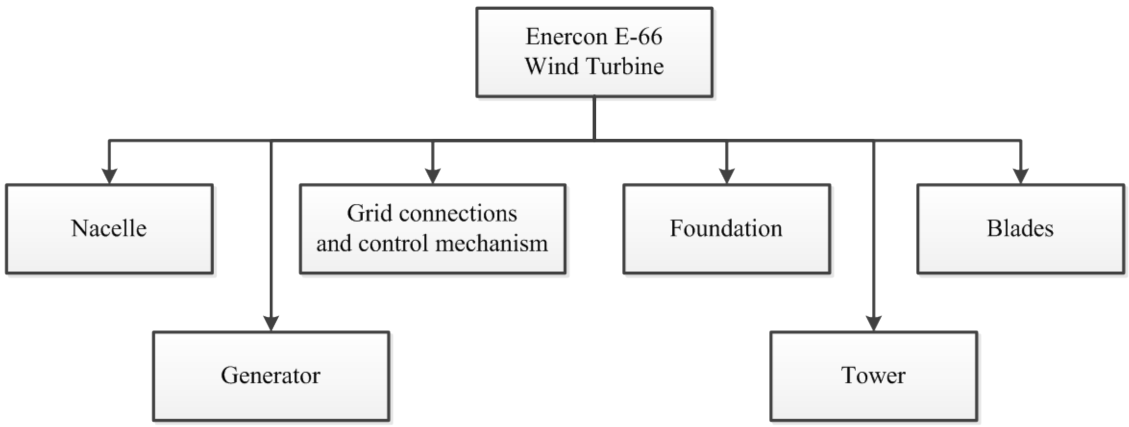


Figure 5-6. Component breakdown of Enercon E-66

A detailed bill of materials (BOM) for the Enercon E-66 is given in Appendix B: Table B-1. It should be highlighted that certain assumptions had to be made since the BOM, though extensive, is not exhaustive. These assumptions are listed in the following section.

(i) Nacelle

The nacelle houses the control mechanisms and electrical generator that regulate the directional controls, blade angles and rotation speeds. It is the point of connection for the nose cone and blades. The nacelle for this turbine model is made up of various steel compounds with iron constituting the majority of the material mass. It also contains small amounts of polyester resin, aluminium and copper. The undefined materials were omitted in the modelling in order not to bias the final results. This of course is presented with the stipulation that no single material in the breakdown of the wind turbine can, on its own, account for a large percentage of the emission and energy impacts of the unit modelled.

(ii) Grid Connection and Control Mechanism

This component covers the units necessary to connect the wind turbine to the local substation, those essential for electricity transmission to the grid, and the control mechanisms contained in the base and nacelle of the wind turbine. The control mechanisms are used to position the nacelle for maximum efficiency, as well as adjust the blades according to the prevalent wind conditions. As a result of the dual nature of this component it consists of various polymers, light weight concrete and large quantities of iron and steel. As there was inadequate information about the difference between certain electronic and electrical components, there was no clear distinction in the databases of the life-cycle modelling software used. As a result, more generic entries in the databases were used that covered a range of electrical components.

(iii) Blades

The blades are the major rotary components of the turbine. The major materials contained in this component are epoxy resin, fibreglass and various plastics. All the materials were accounted for in the databases used with the exception of a quantity of material that was undefined. This undefined entry was replaced by iron, on the assumption that it represented the material requirements for parts such as brackets, bolts, supports etc. For TIO 1 and TIO 4 (use of stiffer carbon fibre materials allowing for tower mass reduction as explained in Section 3.4.2.1), Nylon 66/glass fibre composite (glass-reinforced nylon) was used in the place of fibre glass as it exhibits similar environmental characteristics to carbon fibre. The databases of the life-cycle modelling software did not contain information on entries for carbon fibre resulting in the use of an entry with the closest possible association.

(iv) Tower

The tower supports the main units of the nacelle which include most of the main control mechanisms, the generator and the blades. It consists mainly of steel and a much lesser quantity of galvanized steel, and is the component with the largest quantity of these materials. For TIO 2 and TIO 4 (new tower concepts using carbon fibre materials as explained in Section 3.4.2.2), glass-reinforced nylon was used in the place of steel due to reasons previously described for the blades. Again, the databases of the life-cycle modelling software did not contain information on carbon fibre entries hence the use of the closest possible entry.

(v) Generator

The generator converts the rotational motion of the blades into electrical power. Copper and steel are the materials that mainly comprise the generator. In the case of TIO 3 (use of permanent magnets in the generator instead of copper wound rotors as explained in Section 3.4.2.3.), copper was replaced with iron during entry of the material input into the life-cycle modelling software. Where materials were undefined, they were omitted from the model as it was determined that they account for only 1.2% of generator mass thus there would be minimal impact on the end result.

(vi) Foundation

The foundation provides the base for the tower unit. It mainly consists of concrete and reinforced steel. As there were no undefined materials, no assumptions were required for this component.

Table 5-7. Assumptions used in modelling of Enercon E-66 wind turbine and TIOs 1 - 4

Component	Assumption	Rationale
Nacelle	Undefined materials omitted	To prevent bias of the final results
Grid Connection and Control Mechanism	Generic entries were used to cover range of electrical components	No clear distinction in the difference between electrical components
Blades	Undefined material entry replaced by iron For TIO 2 and 4, glass reinforced nylon used in the place of fibre glass	Used to represent material requirements for parts such as brackets, bolts etc. Closest possible entry in SimaPro software to carbon fibre
Tower	For TIO 2 and TIO 4, glass reinforced nylon used in the place of steel	Closest possible entry in SimaPro software to carbon fibre
Generator	For TIO 3, copper replaced with iron Undefined materials omitted from model	As stated in scenario definition They account for only 1.2% of generator mass
Foundation	No assumptions required	No undefined materials

5.8.3 Energy Requirements for Wind Turbine Manufacture, Assembly and Dismantling

Chataignere and Boulch (2003) provided data on the energy requirements for the manufacture, assembly and dismantling of a 1.5 MW wind turbine. It specified the total primary energy requirement to be 379,734 MJ based on an even split between gas and electricity. Natural gas inputs were given as 2,625 m^3 and electricity requirements given as 26.3 MWh. The end-of-life of the turbine is assumed to require the same energy inputs. The “electricity, medium voltage, production RER, at grid/RER U” option of the Ecoinvent database is the electricity mix considered in order to best represent average European electricity production.

5.8.4 Site Work

This covers the energy and material requirements during the construction of the wind farm. Estimates and assumptions had to be made for this section as there was little available data. The necessary inputs were separated into two categories: inputs related to component transportation from the manufacturing facilities to the site and the inputs related to construction work at the site required to make the wind farm operational.

5.8.4.1 Component Transportation

It is necessary to define the likely transportation routes of the components in order to determine the transportation requirements for construction of the wind farm. As no data existed describing the exact arrival port for the components, assumptions were made as regards the most likely route. The components of the wind turbine are assumed to be transported from the manufacturing facilities in Magdeburg, southern Germany, to Hamburg port, north Germany. Assumed to be covered by road (40t truck), the distance is given as 281 km (Google maps, 2014). From Hamburg the components are then assumed to be transported by container ship to the port of Swansea in Wales, a distance estimated to be about 1277 km (Google maps, 2014). The components are then transported by road (40t truck) to their destination at the Pen y Cymoedd wind farm site, a distance approximated to be 47 km (Google maps, 2014). It should be pointed out that the foundations are assumed to be sourced locally hence are not included as part of the components transported from Germany.

5.8.4.2 On-site Energy Requirements

For construction on site, the use of heavy machinery is required for the wind farm. For the purpose of this study, hydraulic diggers (for preparing the foundations of the wind turbine) and cranes (for erecting the turbines) are assumed to be the main contributors during site construction. According to Elsam Engineering (2004), each wind turbine requires the removal of approximately 450m^3 of earth. In Rydh et al. (2004), the installation of a wind turbine is assumed to require approximately 16 hours of crane work. Chataignere and Boulch (2003) provided data on on-site energy requirements which was given as 556 MJ. This was used to represent diesel for the building machines as there were no details about the nature of this input.

5.8.5 Wind Farm Operation

The operation stage of the wind farm encompasses requirements for keeping the wind farm operational over its lifetime. For the modelling process, some assumptions had to be made as regards the nature of maintenance to be carried out.

5.8.5.1 Component Replacement

Wear and tear, especially of the rotating components, will occur during operation of the wind turbines. The lifetime of the wind farm modelled in this study is 25 years. To be safe, a conservative estimate for maintenance of turbines on the wind farm is assumed based on assumptions in Vestas (2005). Hence during the lifetime of a wind farm, one renewal of half of the generators or the gearboxes must be carried out which is expected to, as a minimum, comprise renewal of the bearings. For the purpose of this study, this assumption was simplified to be a total renewal of half of the generators once in the lifetime of the wind farm.

5.8.5.2 Oils and Lubricants

According to D’Souza et al. (2011), wind turbines require a replacement of lubricant and oils on a regular basis. In this study two assumptions are made based on data in Rydh et al. (2004) and Vestas (2005). Both studies state that each wind turbine requires 320 litres of gear oil for every 5 years of operation and the lubrication requirements for each wind turbine is 16 kg per year.

5.8.5.3 Inspection and Maintenance

The use of a hydraulic crane was added to the modelling process to simulate the actual inspection procedure. To replace the generators, the assumption in Rydh et al. (2004) that each turbine required crane use for 8 hours was used. Inspection requirements were also based on Rydh et al. (2004)'s assumption that every 6 months, a passenger car would inspect the site. The distance travelled for the inspection procedure is assumed to be 120 km based on a round trip from the operations base to the wind farm.

5.8.6 Wind Farm Decommissioning

There is insufficient information about this life cycle stage of wind farms as few wind farms have actually been decommissioned up to now. There is however data on the theoretical disposal of wind turbines to enable the modelling of this stage. The turbines are assumed to be disassembled using a mobile crane and transported 500 km by road (40t truck) to a disposal facility. Energy requirements for dismantling at the facility are assumed to be 2,625 m^3 of natural gas and 26.3 MWh of electricity as stated in Section 5.8.3. The foundations of the turbines are assumed to be left behind on the wind farm site. As already shown in Figure 3-3, the influence of disposing/recycling components of the wind farm was not included in this study.

5.8.7 Cut-off criteria

The cut-off criteria given below were used to make certain that all relevant possible environmental impacts were represented:

- **Energy** - if a flow is less than 1% of the energy at a product-level, then it may be excluded, provided its environmental relevance is not a concern.
- **Mass** - if a flow is less than 1% of the mass at a product-level, then it may be excluded, provided its environmental relevance is not of concern.
- **Environmental relevance** - if a flow meets the above exclusion criteria, but is considered to possibly have a significant environmental impact, it should be included. All material flows leaving 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, should be included.
- The sum of the neglected material flows should not exceed 5% of total energy, mass or environmental relevance, at a product-level.

5.9 Chapter Conclusion

The previous sections have shown the methods employed to create the model for the wind farm. Thus it can be seen that despite the differences in the turbine design variations, similar modelling approaches were adopted. In all cases however where assumptions and approximations were altered, they have been specified to ensure clarity.

Due to the potential for technological advancements to reduce the cost and increase the performance of wind turbines, as stated in Section 3.4.2, their design is a matter of continuous compromise between rival demands. This necessity has had a direct impact on the potential TIOs employed in the wind turbine models. As a result, different scaling relationships and procedures were required to model each design variation while the energy and material inputs did not require specific data collection. Equally, the lack of comprehensive site measurements for the wind farm resulted in the use of a scaling method utilizing data from nearby meteorological stations.

The subsequent models are however believed to reflect conditions at the wind farm site and therefore provide a good basis for computations of the wind power lifecycle using the different design variations.

Chapter 6 Results and Discussion

This chapter presents the results of the integrated methodology, outlined in Chapter 3, for the different wind turbine design variations and wind farm models developed. The chapter is organized such that for each methodological tool used in the assessment, the performance of each design variation is assessed and then compared to the others. The chapter starts in Section 6.1 with a presentation and discussion of the results for the uncertainty analysis as this was conducted for a single wind turbine. This is followed by presentation and discussion of results for the wind farm lifecycle using the different design variations in Section 6.2. Finally, Section 6.3 presents and discusses the economics as regards the use of each design variation on the wind farm.

6.1 Uncertainty Analysis

This section addresses the data uncertainty quantification aspect of the sustainability assessment. Estimation of the embodied energy and embodied carbon for the different wind turbine design variations was performed. The composition of materials data for the baseline turbine and TIOs 1 - 4, presented in Appendix A: Tables A-1 to A-5, formed the basis for deterministic estimation of the embodied energy and embodied carbon. Since the material quantities were taken from the same source, they have little or no variations. The deterministic result estimate (Appendix A: Table A-6) is used as a point of reference for comparing outputs of the stochastic estimation. The results are presented and discussed in the sections below.

6.1.1 Quantitative DQI Transformation

To appropriately transform the qualitative assessment results to the equivalent quantitative probability density functions, Wang and Shen (2013) suggests that the aggregated DQI scores be approximated to the nearest nominal value so as to use the transformation matrix. Table 6-1 shows the obtained aggregated DQI scores, for the baseline turbine, following the method described in Section 3.6.2.1. The quantitative DQI procedure was then used to transform the scores into Beta distributions, results of which are shown in Table 6-1. Most of the data used in the study are of good quality and were taken from the same data source and hence showed identical transformed Beta function parameters ($\alpha = 4$, $\beta = 4$), the same DQI score of 4.5 and range end points of ± 15%. The exceptions were Cast iron EF, Cast iron EEC and Gear oil EEC showing DQI scores of 3.5, transformed Beta function parameters of ($\alpha = 2$, $\beta = 2$) and range end points of ± 25% making them more uncertain.

Table 6-1. Transformation of DQI scores to probability density functions

EF Parameters	**Beta (α, β)**	**Range endpoints**	**EEC Parameters**	**Beta (α, β)**	**Range endpoints**
Aluminium (EF)	(4, 4)	(+/-15%) ≈ (1.7, 2.3)	Aluminium (EEC)	(4, 4)	(+/-15%) ≈ (131.8, 178.3)
Fibre glass (EF)	(4, 4)	(+/-15%) ≈ (6.9, 9.3)	Fibre glass (EEC)	(4, 4)	(+/-15%) ≈ (85, 115)
Epoxy resin (EF)	(4, 4)	(+/-15%) ≈ (5, 6.8)	Epoxy resin (EEC)	(4, 4)	(+/-15%) ≈ (118, 160)
Polyethene (EF)	(4, 4)	(+/-15%) ≈ (1.7, 2.2)	Polyethene (EEC)	(4, 4)	(+/-15%) ≈ (70.6, 95.6)
PVC (EF)	(4, 4)	(+/-15%) ≈ (2.1, 2.8)	PVC (EEC)	(4, 4)	(+/-15%) ≈ (65.6, 88.8)
Paint (EF)	(4, 4)	(+/-15%) ≈ (3, 4.1)	Paint (EEC)	(4, 4)	(+/-15%) ≈ (57.8, 78.2)
Rubber (EF)	(4, 4)	(+/-15%) ≈ (2.7, 3.7)	Rubber (EEC)	(4, 4)	(+/-15%) ≈ (86.4, 117)
Iron (EF)	(4, 4)	(+/-15%) ≈ (1.6, 2.2)	Iron (EEC)	(4, 4)	(+/-15%) ≈ (21.3, 28.8)
Steel (EF)	(4, 4)	(+/-15%) ≈ (2.3, 3.2)	Steel (EEC)	(4, 4)	(+/-15%) ≈ (20.7, 28)
Galvanized steel (EF)	(4, 4)	(+/-15%) ≈ (2.4, 3.2)	Galvanized steel (EEC)	(4, 4)	(+/-15%) ≈ (33.2, 45)
Copper (EF)	(4, 4)	(+/-15%) ≈ (3.3, 4.4)	Copper (EEC)	(4, 4)	(+/-15%) ≈ (42.5, 57.5)
Steel sheet (EF)	(4, 4)	(+/-15%) ≈ (2.1, 2.9)	Steel sheet (EEC)	(4, 4)	(+/-15%) ≈ (27, 36.2)
Steel (no alloy) (EF)	(4, 4)	(+/-15%) ≈ (1.5, 2)	Steel (no alloy) (EEC)	(4, 4)	(+/-15%) ≈ (29.2, 39.6)
Steel (alloy, high grade) (EF)	(4, 4)	(+/-15%) ≈ (2.4, 3.2)	Steel (alloy, high grade) (EEC)	(4, 4)	(+/-15%) ≈ (48.2, 65.2)
Steel (alloy, low grade) (EF)	(4, 4)	(+/-15%) ≈ (2.3, 3.1)	Steel (alloy, low grade) (EEC)	(4, 4)	(+/-15%) ≈ (41, 55.7)
Cast Steel (EF)	(4, 4)	(+/-15%) ≈ (2.4, 3.3)	Cast Steel (EEC)	(4, 4)	(+/-15%) ≈ (21.6, 29.2)
Cast iron (EF)	(2, 2)	(+/-25%) ≈ (1.4, 2.4)	Cast iron (EEC)	(2, 2)	(+/-25%) ≈ (19.5, 32.5)
Unsaturated polyester resin (EF)	(4, 4)	(+/-15%) ≈ (1.7, 2.2)	Unsaturated polyester resin (EEC)	(4, 4)	(+/-15%) ≈ (96.1, 130)
Electronics (EF)	(4, 4)	(+/-15%) ≈ (2.3, 3.1)	Electronics (EEC)	(4, 4)	(+/-15%) ≈ (68.4, 92.6)
Steel (for construction) (EF)	(4, 4)	(+/-15%) ≈ (0.6, 0.8)	Steel (for construction) (EEC)	(4, 4)	(+/-15%) ≈ (30.6, 41.4)
Gear oil (EF)	(4, 4)	(+/-15%) ≈ (3.1, 4.2)	Gear oil (EEC)	(2, 2)	(+/-25%) ≈ (41.3, 69)
Light weight concrete (EF)	(4, 4)	(+/-15%) ≈ (0.1, 0.2)	Light weight concrete (EEC)	(4, 4)	(+/-15%) ≈ (0.7, 0.9)
Normal concrete (EF)	(4, 4)	(+/-15%) ≈ (0.17, 0.23)	Normal concrete (EEC)	(4, 4)	(+/-15%) ≈ (1.2, 1.6)

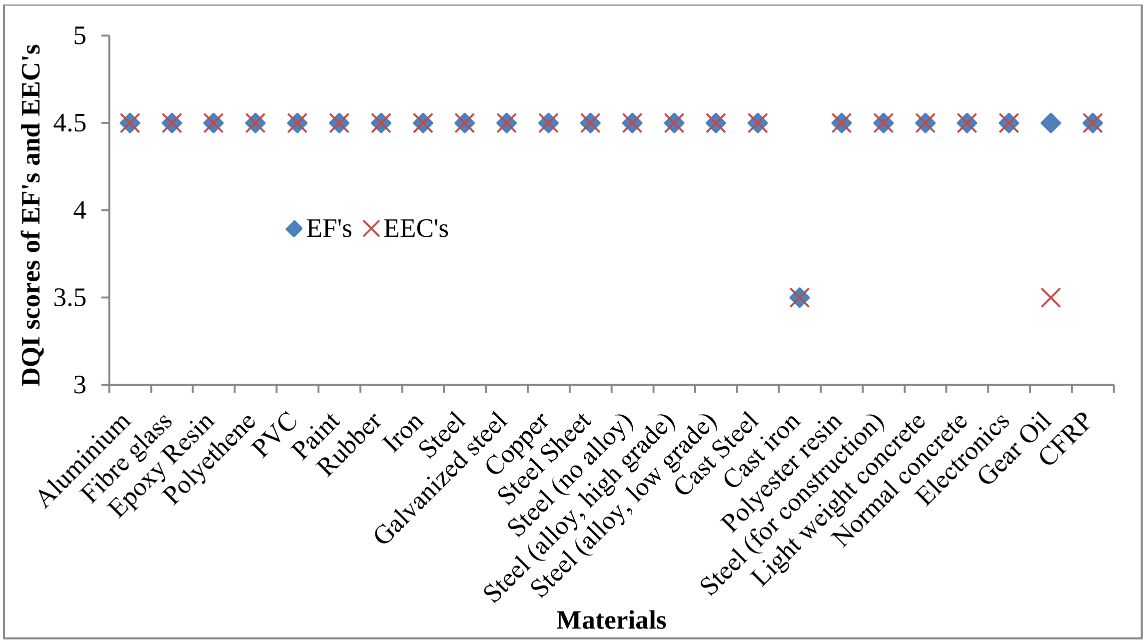


Figure 6-1. Aggregated DQI scores for emission factors and embodied energy coefficients

6.1.2 Parameter Categorization and Probability Distributions Estimation

Results of the influence analysis (10,000 iterations MCS) showing the two parameters contributing the most to the resulting uncertainty is presented in Table 6-2. Two parameters, Steel and Carbon fibre reinforced plastic (CFRP), demonstrated the largest influence on the final resulting uncertainty of embodied energy and embodied carbon across all case studies. For the parameters with a lesser contribution to the final resulting uncertainty, there were variations across all case studies. Normal concrete and CFRP show the lesser contribution for embodied carbon, while Steel (no alloy), CFRP and Cast iron show the lesser contribution for embodied energy across all case studies. Combining these results, further analysis was conducted on the two identified parameters for each test case using the statistical method, while the values for the remaining parameters were obtained from the quantitative DQI. Probability distributions were thus fitted to data points collected manually from literature. Results of the estimated probability distributions for the different parameters are presented in Table 6-3.

Table 6-2. Influence Analysis

	Embodied Carbon	**Influence (%)**	**Embodied Energy**	**Influence (%)**
Baseline Turbine	Steel EF	78	Steel EEC	62
	Normal concrete EF	9	Steel (no alloy) EEC	9
TIO 1	Steel EF	66	Steel EEC	47
	CFRP EF	17	CFRP EEC	22
TIO 2	CFRP EF	99	CFRP EEC	97
	Normal concrete EF	0.3	Steel (no alloy) EEC	0.7
TIO 3	Steel EF	81	Steel EEC	66
	Normal concrete EF	8	Cast iron EEC	9
TIO 4	CFRP EF	98	CFRP EEC	97
	Normal concrete EF	0.6	Steel (no alloy) EEC	0.5

Table 6-3. Probability distribution estimation for the different parameters

Parameter	**Probability Distribution**	**Mean**	**Data points collected**	**Source**
Steel EF Steel EEC	Beta (1.24, 4.47) Beta (2.96, 4.16)	1.73 tonCO_2/ton 25.87 GJ/ton	30 31	Hammond and Jones, 2008; Fleck and Huot, 2009; Alcorn and Wood, 1998; Norgate et al., 2007; Rankine et al., 2006; Khan et al., 2005; Change, 2006; Hammond and Jones, 2011; Lee et al., 2011; Baird et al., 1997
Normal concrete EF	Beta (20.8, 87.7)	0.11 tonCO_2/ton	31	Hammond and Jones, 2008; Hammond and Jones, 2011; Alcorn and Wood, 1998; Norgate et al., 2007; Rankine et al., 2006
Steel (no alloy) EEC	Beta (48.6, 62.3)	25.57 GJ/ton	31	Hammond and Jones, 2008; Alcorn and Wood, 1998; Norgate et al., 2007; Rankine et al., 2006; Khan et al., 2005; Change, 2006; Lee et al., 2011; Baird et al., 1997; Fernando, 2010
CFRP EF CFRP EEC	Beta (3.16, 2.2) Beta (2.13, 6.23)	52.4 tonCO_2/ton 191.3 GJ/ton	31 31	Hill et al., 2011; Kirihara et al., 2011; Pimenta and Pinho, 2011; Howarth et al., 2014; Douglas et al., 2008; Song et al., 2009; Rydh and Sun, 2005; Duflou et al., 2012
Cast iron EEC	Beta (36.6, 75.2)	35.4 GJ/ton	31	Fernando, 2010; Du et al., 2012; TERI, 2012; Hendrickson and Horvath, 2014; Sharma et al., 2013; Baum et al., 2009; Sefeedpari et al., 2012; Lenzen and Dey, 2000; Lenzen and Treloar, 2002; Baird et al., 1997

6.1.3 Stochastic Results Comparison of DQI and HDS Approaches for the Different Case Studies

Embodied carbon and embodied energy stochastic results (10,000 iterations MCS) using the pure DQI and HDS methods were obtained for the baseline turbine and TIO's 1 - 4 the results of which are presented in this section. Results for each case study are presented graphically through probability distribution functions (PDF's) and cumulative distribution functions (CDF's) in Figures 6-2 to 6-11. In addition to these figures, MRE and CV values were also calculated. A summary of the relevant information is provided in Table 6-4.

Table 6-4. Pure DQI and HDS results for the different case studies

	Embodied Carbon		**Embodied Energy**	
	DQI	**HDS**	**DQI**	**HDS**
Baseline Turbine	Beta distribution (4.5, 5.3) μ = 932 tonCO_2 σ = 22 tonCO_2 CV = 0.02	Beta distribution (1.8, 5.1) μ = 733 tonCO_2 σ = 183 tonCO_2 CV = 0.25 MRE = 27%	Normal distribution μ = 11909 GJ σ =218 GJ CV = 0.02	Beta distribution (4.4, 4.7) μ = 11831 GJ σ = 1424 GJ CV = 0.12 MRE = 1%
TIO 1	Normal distribution μ =1070 tonCO_2 σ = 24 tonCO_2 CV = 0.02	Beta distribution (2.3, 5.2) μ =1269 tonCO_2 σ =188 tonCO_2 CV = 0.15 MRE = 16%	Normal distribution μ = 13735 GJ σ = 244 GJ CV = 0.02	Beta distribution (3.8, 4.7) μ = 13276 GJ σ = 1469 GJ CV = 0.11 MRE = 3.5%
TIO 2	Beta distribution (5, 5.3) μ = 2475 tonCO_2 σ = 96 tonCO_2 CV = 0.04	Beta distribution (5.8, 4.1) μ = 5521 tonCO_2 σ = 1654 tonCO_2 CV = 0.3 MRE = 55%	Beta distribution (4.1, 4.8) μ = 31822 GJ σ = 1166 GJ CV = 0.04	Beta distribution (2.4, 4.7) μ =24687 GJ σ = 7608 GJ CV = 0.3 MRE = 29%
TIO 3	Beta distribution (5.3, 5.7) μ = 849 tonCO_2 σ = 22 tonCO_2 CV = 0.03	Beta distribution (1.6, 4.6) μ = 647 tonCO_2 σ =185 tonCO_2 CV = 0.29 MRE = 31%	Normal distribution μ =10722 GJ σ =211 GJ CV = 0.02	Beta distribution (3.8, 4.8) μ =11249 GJ σ = 1474 GJ CV = 0.13 MRE = 5%
TIO 4	Gamma distribution (529, 4.8) μ = 2529 tonCO_2 σ = 108 tonCO_2 CV = 0.04	Weibull distribution (3.96, 6621) μ = 5988 tonCO_2 σ = 1746 tonCO_2 CV = 0.29 MRE = 58%	Beta distribution (4.7, 4.5) μ = 32503 GJ σ = 1304 GJ CV = 0.04	Beta distribution (2.1, 4.6) μ = 24299 GJ σ = 8419 GJ CV = 0.35 MRE = 33%

6.1.3.1 Baseline Turbine

Figures 6-2 and 6-3 show the stochastic results (10,000 runs MCS) for embodied carbon and embodied energy using the HDS and DQI methods. For embodied carbon, Beta distribution (4.5, 5.3) was fitted, according to K-S test, to the DQI result with a mean value of 932 tonCO_2 and a standard deviation of 22 tonCO_2. The HDS follows Beta distribution (1.8, 5.1) (K-S test), with a mean value of 733 tonCO_2 and standard deviation of 183 tonCO_2 thus having a larger spread compared to the DQI result. The CV value of the HDS result is 0.25, 1250% larger than the DQI result CV value of 0.02. The (10%, 90%) certainty interval for the output of the DQI result is (904 tonCO_2, 960 tonCO_2) with a span of 56 tonCO_2, while the HDS presents a much greater (10%, 90%) certainty interval of (535 tonCO_2, 992 tonCO_2) with a span of 458 tonCO_2. In terms of MRE, a 27% difference was observed between the HDS and pure DQI results showing that the HDS approach captured more possible outcomes compared to the pure DQI. The differences in the results can also be deduced from the CDF (Figure 6-2b). For the HDS result, about 85% of the likely results are smaller than the obtained deterministic result while for the DQI result, 50% of the likely resulting values are smaller than the obtained deterministic result.

For embodied energy, Normal distribution with a mean value of 11909 GJ and standard deviation of 218 GJ was fitted, according to K-S test, to the DQI result. The HDS result follows Beta distribution (4.4, 4.7) (K-S test), with a mean value of 11831 GJ and standard deviation of 1424 GJ. The CV value of the HDS result is 0.12 compared to 0.02 for the pure DQI result. The (10%, 90%) certainty interval for the HDS output is (9918 GJ, 13799 GJ) with a span of 3880 GJ while the (10%, 90%) certainty interval for the DQI output is (11625 GJ, 12187 GJ) with a span of 562 GJ. For the MRE, a 1% difference was observed between the DQI and HDS results. The CDF (Figure 6-3b) shows half of the likely resulting values are smaller than the obtained deterministic result for both the DQI and HDS results.

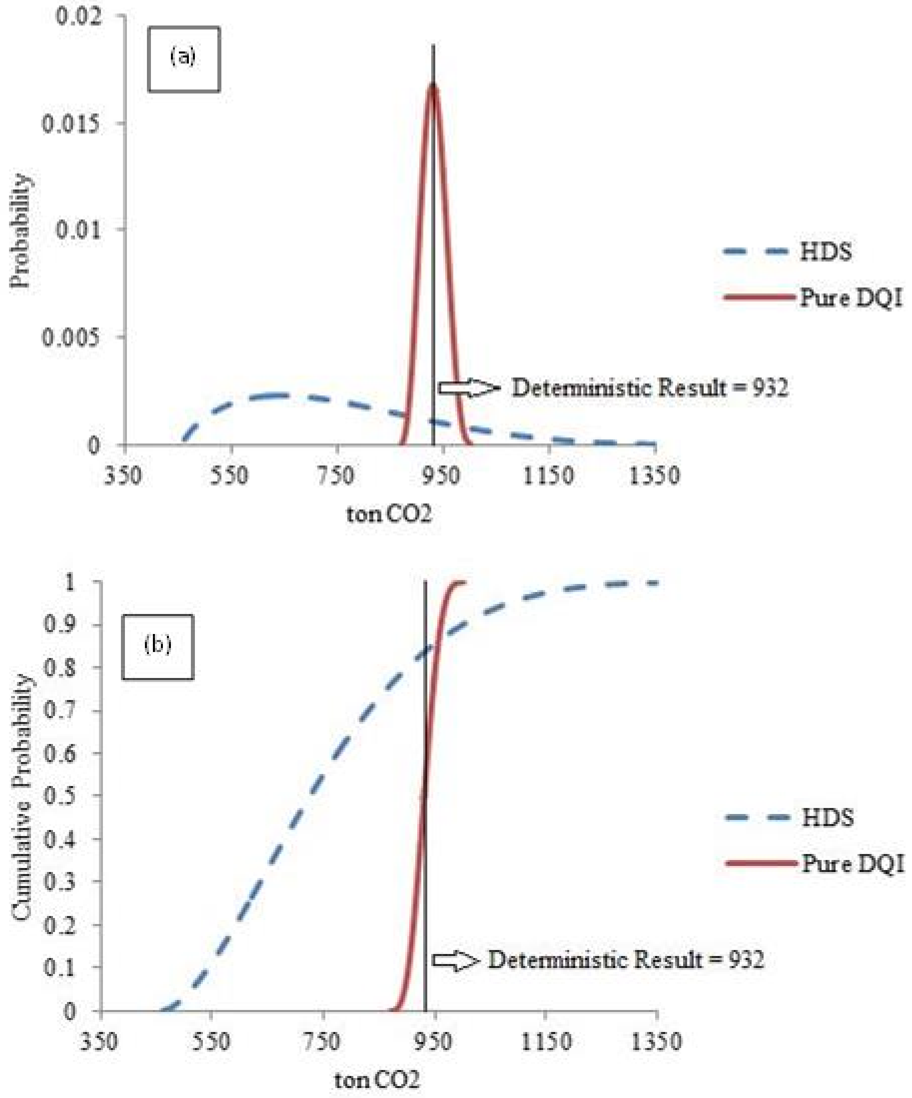


Figure 6-2. (a) Baseline Turbine Embodied Carbon PDF results; (b) Baseline Turbine Embodied Carbon CDF results

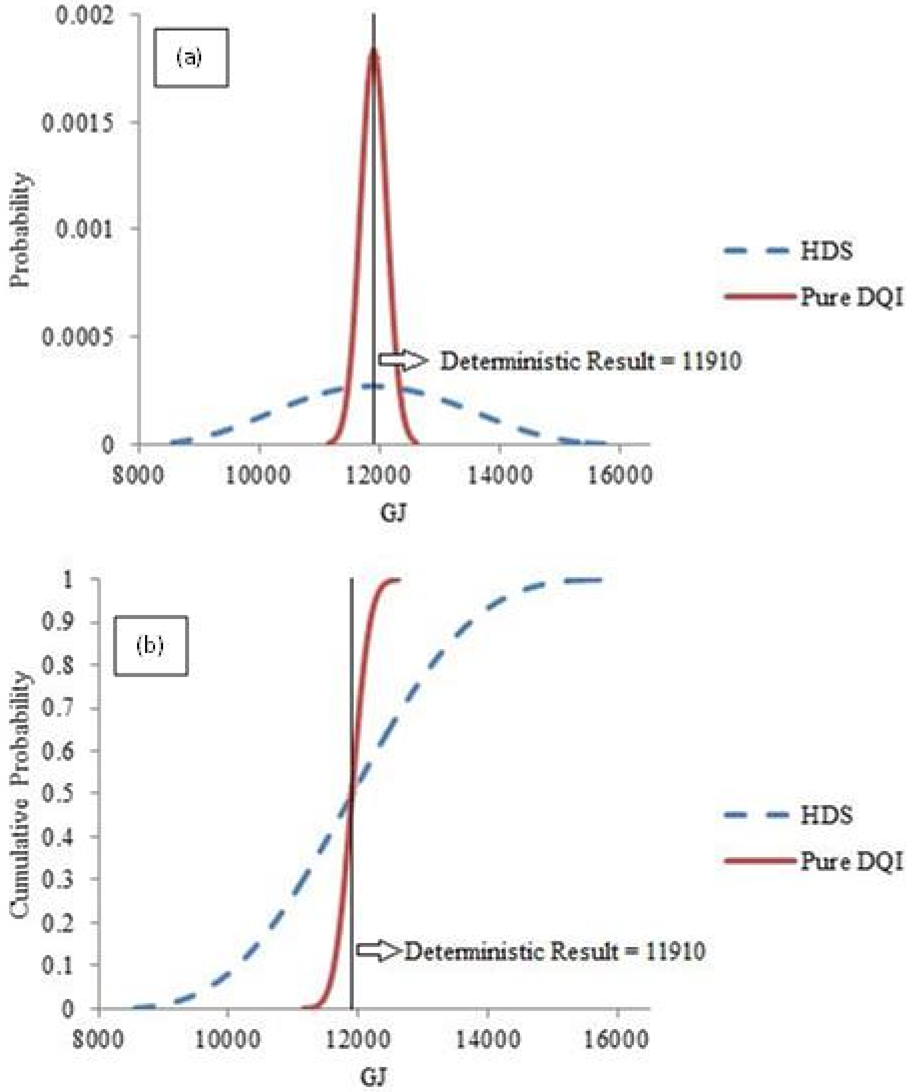


Figure 6-3. (a) Baseline Turbine Embodied Energy PDF results; (b) Baseline Turbine Embodied Energy CDF results

6.1.3.2 TIO 1

For embodied carbon, a Normal distribution with mean value of 1070 tonCO_2 and standard deviation of 24 tonCO_2 (K-S test) was fitted to the DQI result. Beta distribution (2.3, 5.2) (K-S test), with a mean value of 1269 tonCO_2 and standard deviation of 188 tonCO_2 was fitted to the HDS result thus having a larger dispersion compared to the DQI result. The CV value of the HDS result is 0.15, which is larger than the DQI result CV value of 0.02. The (10%, 90%) certainty interval for the output of the DQI result is (1037 tonCO_2, 1101 tonCO_2) with a span of 64 tonCO2, while the HDS presents a much greater (10%, 90%) certainty interval of (1066 tonCO_2, 1565 tonCO_2) with a span of 500 tonCO_2. In terms of MRE, a difference of 16% was observed between the HDS and pure DQI results. It is seen from the CDF (Figure 6-4b) that for the HDS result, about 15% of the possible results are smaller than the obtained deterministic result. While for the DQI result, 50% of the possible resulting values are smaller than the obtained deterministic result.

For the embodied energy, a Normal distribution with mean value of 13735 GJ and standard deviation of 244 GJ (K-S test) was fitted to the DQI result. The HDS result follows Beta distribution (3.8, 4.7) (K-S test), with a mean value of 13276 GJ and standard deviation of 1469 GJ. The CV value of the HDS result is 0.11 compared to 0.02 for the pure DQI result. The (10%, 90%) certainty interval for the HDS output is (11345 GJ, 15333 GJ) with a span of 3988 GJ while the (10%, 90%) certainty interval for the DQI output is (13407 GJ, 14058 GJ) with a span of 652 GJ. For the MRE, a 3.5% difference was observed between the DQI and HDS results. The CDF (Figure 6-5b) shows that for the HDS result about 60% of the possible results are smaller than the obtained deterministic result while for the DQI result, 50% of the possible resulting values are smaller than the obtained deterministic result.

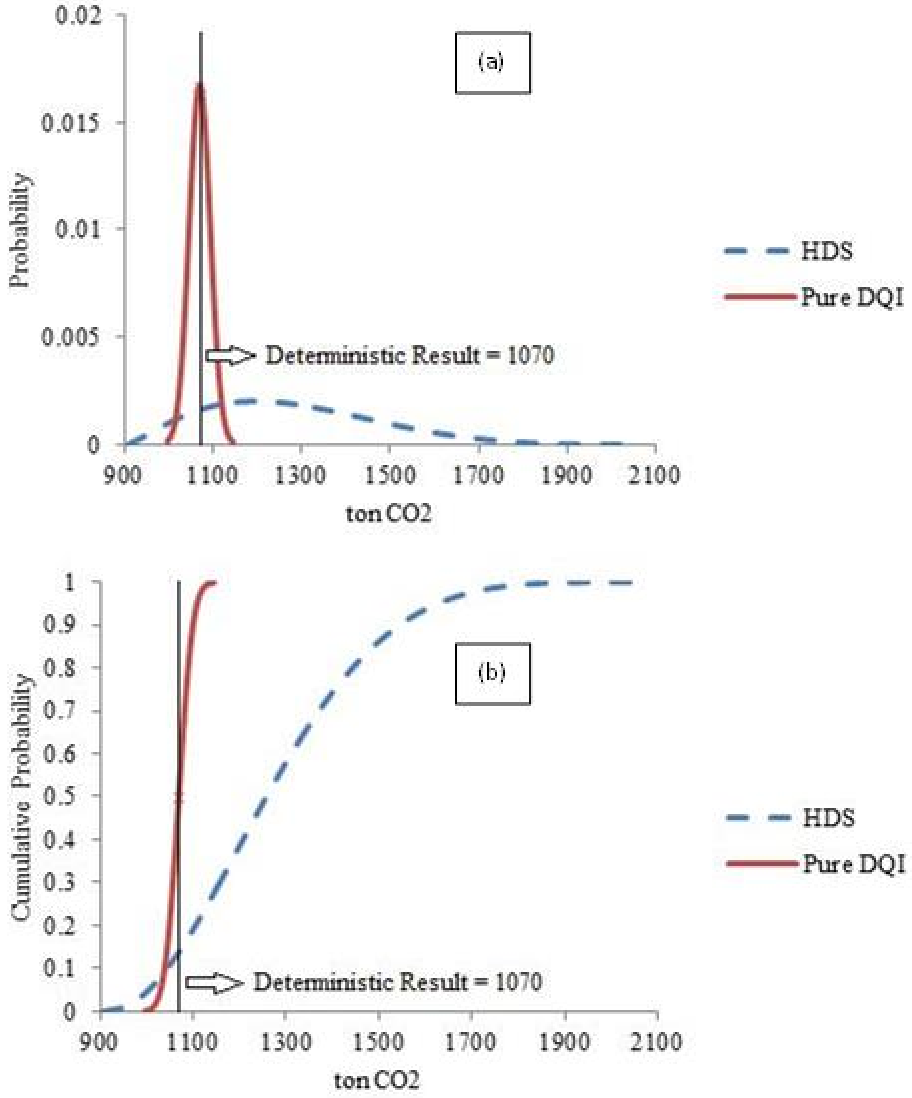


Figure 6-4. (a) TIO 1 Embodied Carbon PDF results; (b) TIO 1 Embodied Carbon CDF results

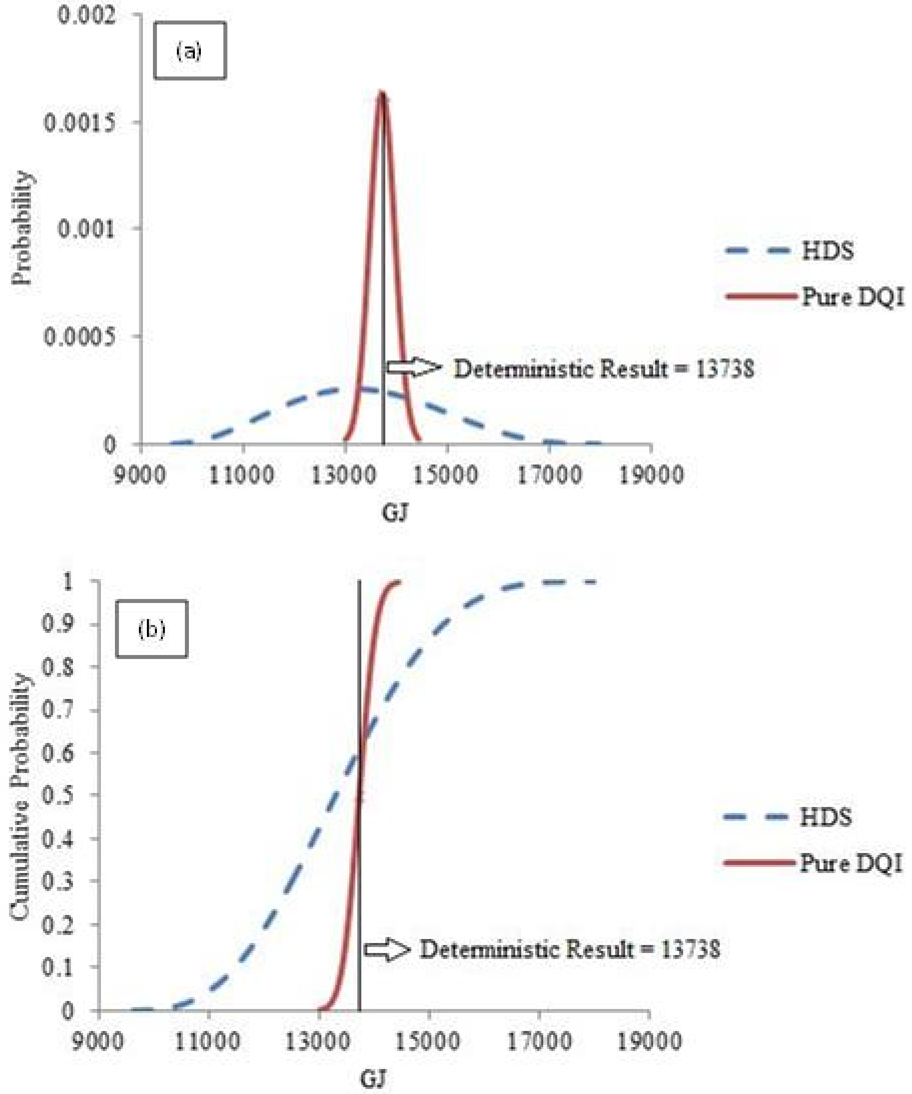


Figure 6-5. (a) TIO 1 Embodied Energy PDF results; (b) TIO 1 Embodied Energy CDF results

6.1.3.3 TIO 2

For embodied carbon, Beta distribution (5, 5.3) (K-S test), with a mean value of 2475 tonCO_2 and standard deviation of 96 tonCO_2 was fitted to the DQI result. Beta distribution (5.8, 4.1) (K-S test), with a mean value of 5521 tonCO_2 and standard deviation of 1654 tonCO_2 was fitted to the HDS result thus having a larger dispersion than the DQI result. The CV value of the HDS result is 0.3, which is larger than the DQI result CV value of 0.04. The (10%, 90%) certainty interval for the output of the DQI result is (2345 tonCO_2, 2606 tonCO_2) with a span of 261 tonCO_2, while the HDS presents a much larger (10%, 90%) certainty interval of (3153 tonCO_2, 7722 tonCO_2) with a span of 4568 tonCO_2. In terms of MRE, a 55% difference was observed between the HDS and pure DQI results. It is seen from the CDF (Figure 6-6b) that for the HDS result, about 0.01% of the likely results are smaller than the obtained deterministic result. While for the DQI result, 50% of the likely resulting values are smaller than the obtained deterministic result.

For the embodied energy, Beta distribution (4.1, 4.8) (K-S test), with mean value of 31822 GJ and standard deviation of 1166 GJ was fitted to the DQI result. The HDS result follows Beta distribution (2.4, 4.7) (K-S test), with a mean value of 24687 GJ and standard deviation of 7608 GJ. The CV value of the HDS result is 0.3 compared to 0.04 for the pure DQI result. The (10%, 90%) certainty interval for the HDS output is (15704 GJ, 35845 GJ) with a span of 20141 GJ while the (10%, 90%) certainty interval for the DQI output is (30231 GJ, 33399 GJ) with a span of 3169 GJ. For the MRE, a 29% difference was observed between the DQI and HDS results. For the HDS result the CDF (Figure 6-7b) shows about 85% of the possible results are smaller than the obtained deterministic result while for the DQI result, half of the possible resulting values are smaller than the obtained deterministic result.

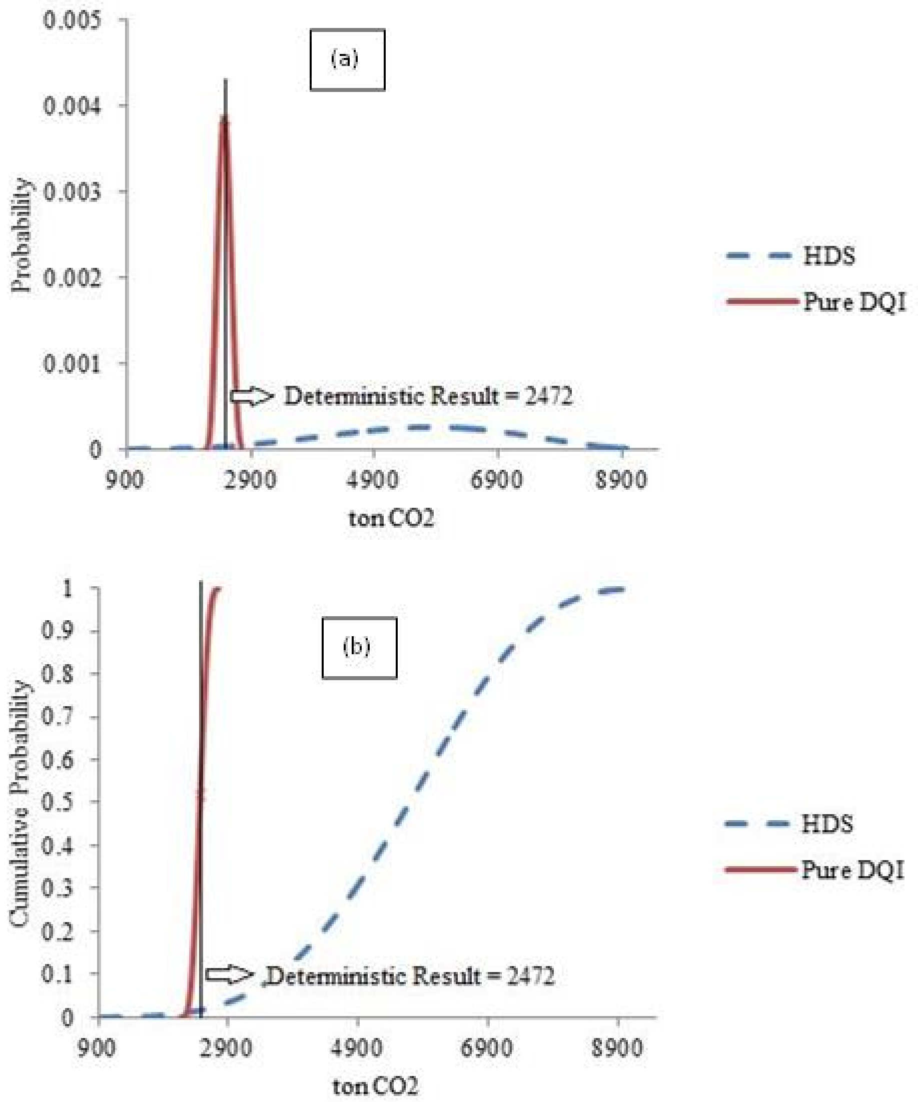
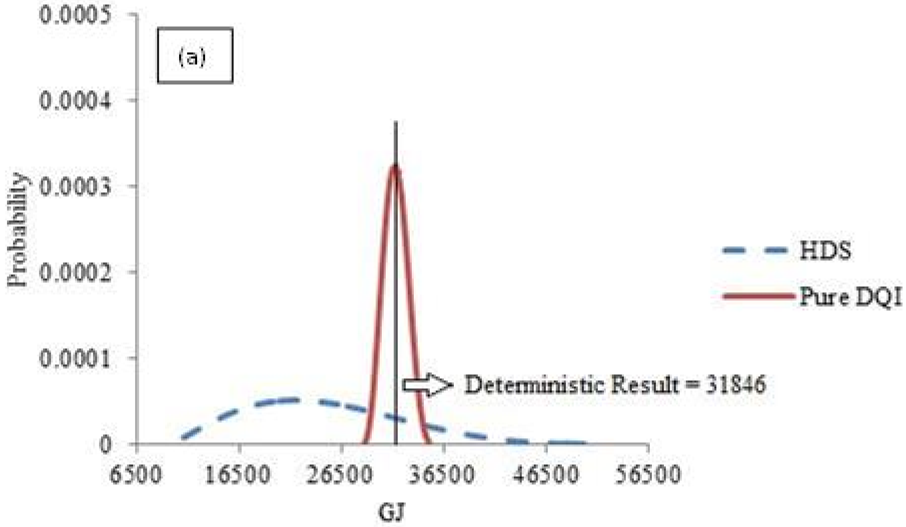


Figure 6-6. (a) TIO 2 Embodied Carbon PDF results; (b) TIO 2 Embodied Carbon CDF results



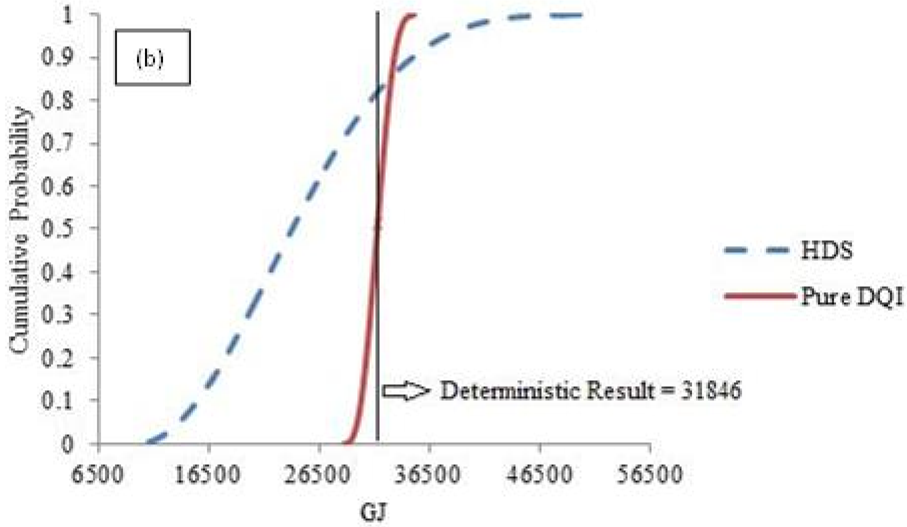


Figure 6-7. (a) TIO 2 Embodied Energy PDF results; (b) TIO 2 Embodied Energy CDF results

6.1.3.4 TIO 3

For embodied carbon Beta distribution (5.3, 5.7) was fitted, according to K-S test, to the DQI result with a mean value of 849 tonCO_2 and a standard deviation of 22 tonCO_2. The HDS follows Beta distribution (1.6, 4.6) (K-S test), with a mean value of 647 tonCO_2 and standard deviation of 185 tonCO_2 thus having a larger dispersion compared to the DQI result. The CV value of the HDS result is 0.3, which is larger than the DQI result CV value of 0.03. The (10%, 90%) certainty interval for the output of the DQI result is (820 tonCO_2, 878 tonCO_2) with a span of 58 tonCO_2, while the HDS presents a much larger (10%, 90%) certainty interval of (454 tonCO_2, 920 tonCO_2) with a span of 467 tonCO_2. In terms of MRE, a 31% difference was observed between the HDS and pure DQI results. It is seen from the CDF (Figure 6-8b) that for the HDS result, about 85% of the possible results are smaller than the obtained deterministic result. While for the DQI result, 50% of the possible resulting values are smaller than the obtained deterministic result.

For the embodied energy, a Normal distribution with mean value of 10722 GJ and standard deviation of 211 GJ (K-S test) was fitted to the DQI result. The HDS result follows Beta distribution (3.8, 4.8) (K-S test), with a mean value of 11249 GJ and standard deviation of 1474 GJ. The CV value of the HDS result is 0.13 compared to 0.02 for the pure DQI result. The (10%, 90%) certainty interval for the HDS output is (9268 GJ, 13346 GJ) with a span of 4078 GJ while the (10%, 90%) certainty interval for the DQI output is (10457 GJ, 10986 GJ) with a span of 529 GJ. For the MRE, a 5% difference was observed between the DQI and HDS results. The CDF (Figure 6-9b) shows about 35% of the possible results are smaller than the obtained deterministic result while for the DQI result, half of the possible resulting values are smaller than the obtained deterministic result.

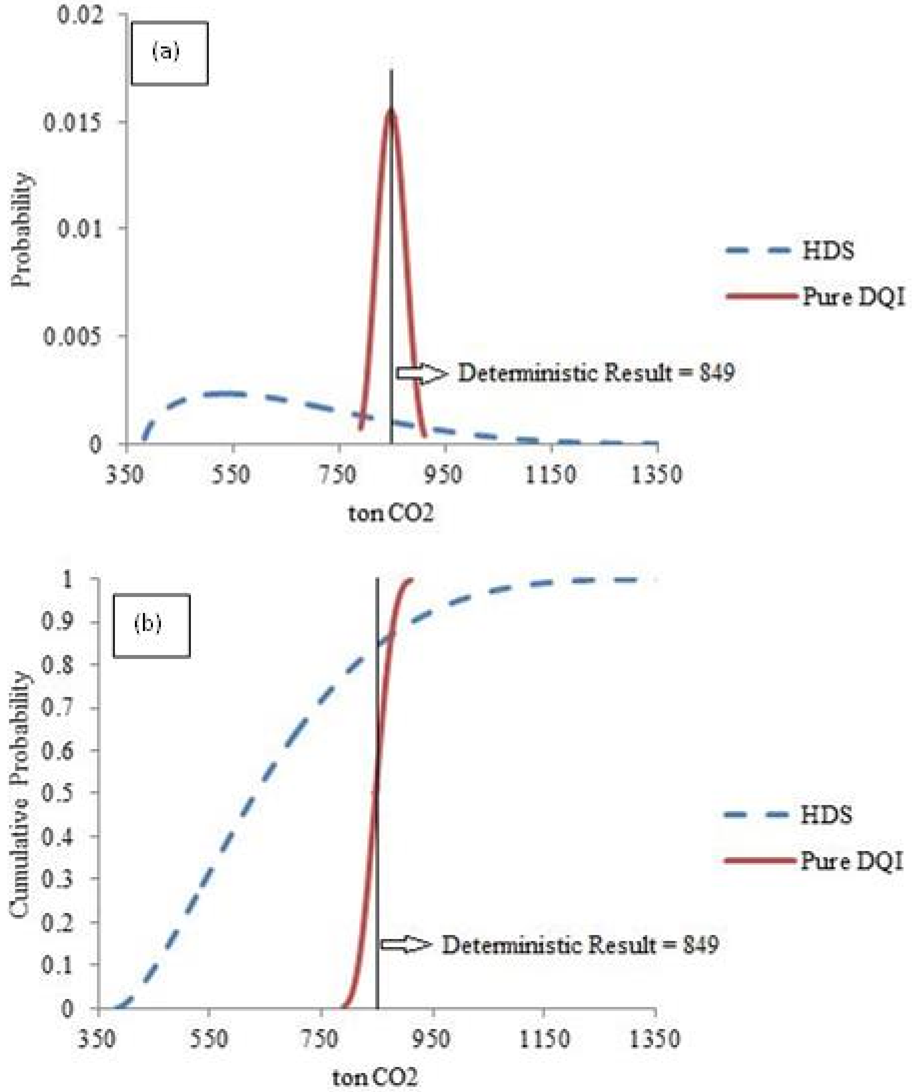
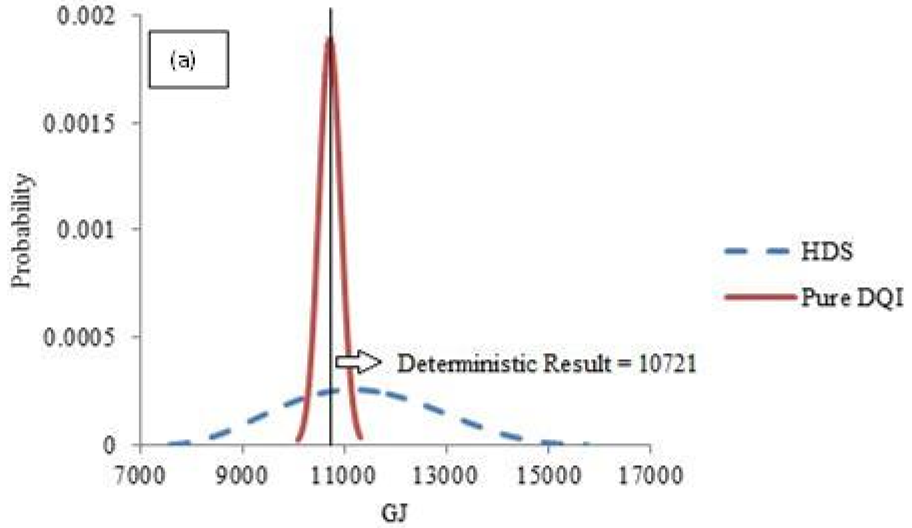


Figure 6-8. (a) TIO 3 Embodied Carbon PDF results; (b) TIO 3 Embodied Carbon CDF results



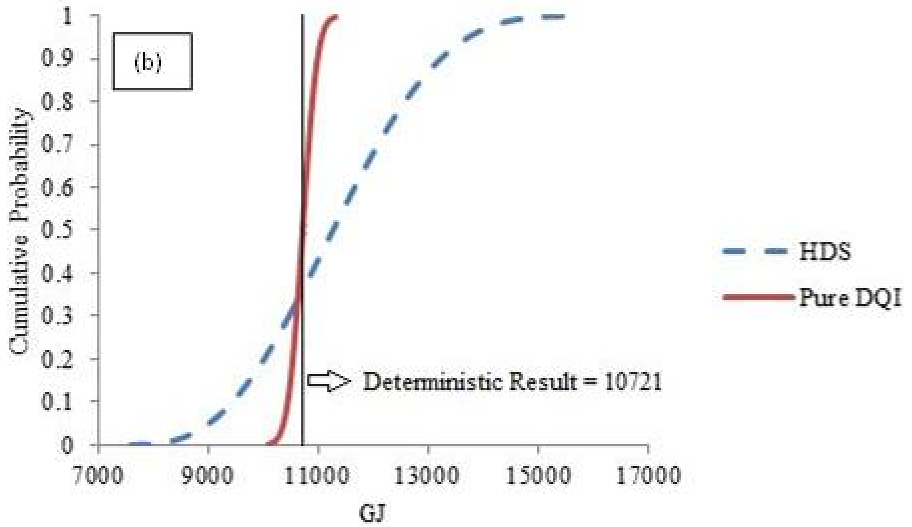


Figure 6-9. (a) TIO 3 Embodied Energy PDF results; (b) TIO 3 Embodied Energy CDF results

6.1.3.5 TIO 4

Results for the embodied carbon show Gamma distribution (529, 4.8) was best fitted, according to K-S test, to the DQI result with a mean value of 2529 tonCO_2 and a standard deviation of 108 tonCO_2. The HDS follows Weibull distribution (3.96, 6621) (K-S test), with a mean value of 5988 tonCO_2 and standard deviation of 1746 tonCO_2. The CV value of the HDS result is 0.29, which is larger than the DQI result CV value of 0.04. The (10%, 90%) certainty interval for the output of the DQI result is (2381 tonCO_2, 2671 tonCO_2) with a span of 289 tonCO_2, while the HDS presents a much greater (10%, 90%) certainty interval of (3599 tonCO_2, 8245 tonCO_2) with a span of 4646 tonCO_2. In terms of MRE, a 58% difference was observed between the HDS and pure DQI results. It is seen from the CDF (Figure 6-10b) that for the HDS result, about 0.01% of the possible results are smaller than the obtained deterministic result. For the DQI result, 50% of the possible resulting values are smaller than the obtained deterministic result.

Results for the embodied energy show Beta distribution (4.7, 4.5) was best fitted, according to K-S test, to the DQI result with a mean value of 32503 GJ and a standard deviation of 1304 GJ. The HDS result follows Beta distribution (2.1, 4.6) (K-S test), with a mean value of 24299 GJ and standard deviation of 8419 GJ. The CV value of the HDS result is 0.35 compared to 0.04 for the pure DQI result. The (10%, 90%) certainty interval for the HDS output is (14097 GJ, 36263 GJ) with a span of 22165 GJ while the (10%, 90%) certainty interval for the DQI output is (30725 GJ, 34283 GJ) with a span of 3558 GJ. For the MRE, a 33% difference was observed between the DQI and HDS results. The CDF (Figure 6-11b) shows about 85% of the possible results are smaller than the obtained deterministic result while for the DQI result, half of the possible resulting values are smaller than the obtained deterministic result.

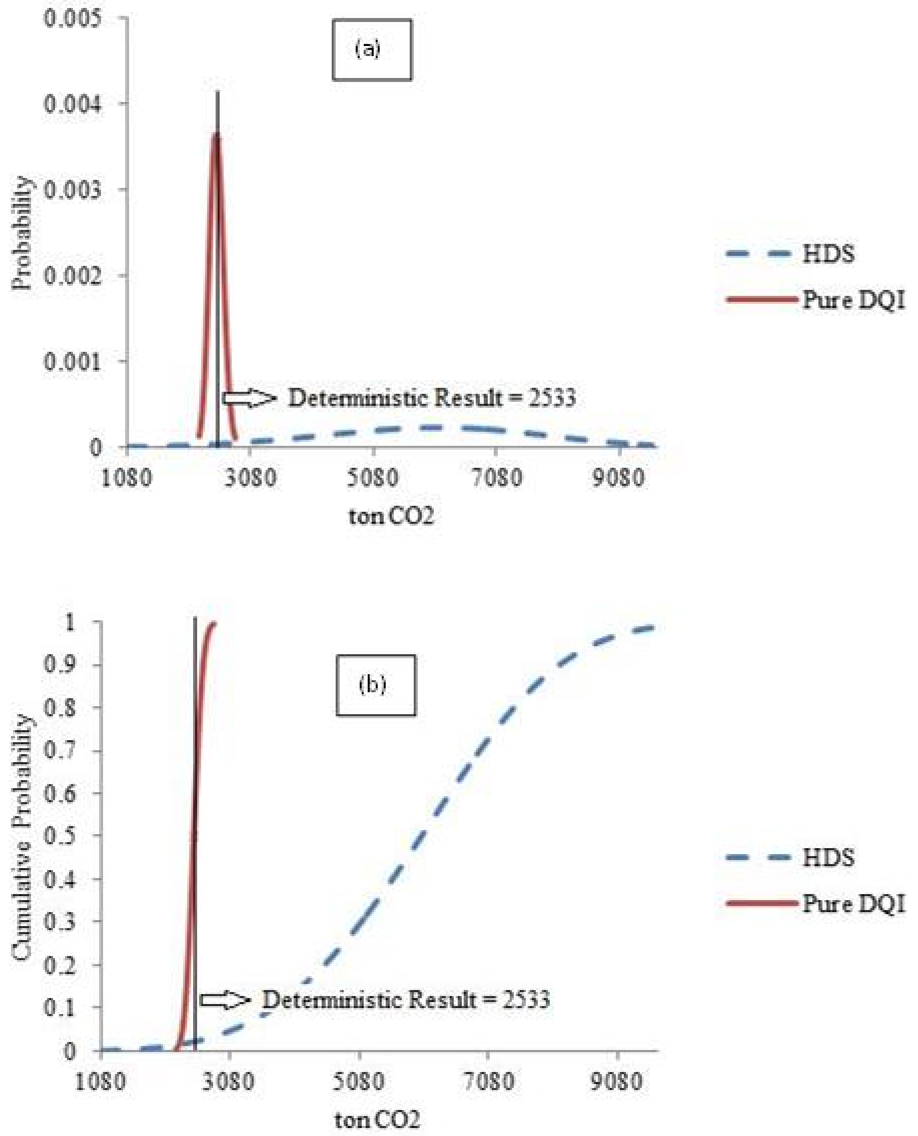


Figure 6-10. (a) TIO 4 Embodied Carbon PDF results; (b) TIO 4 Embodied Carbon CDF results

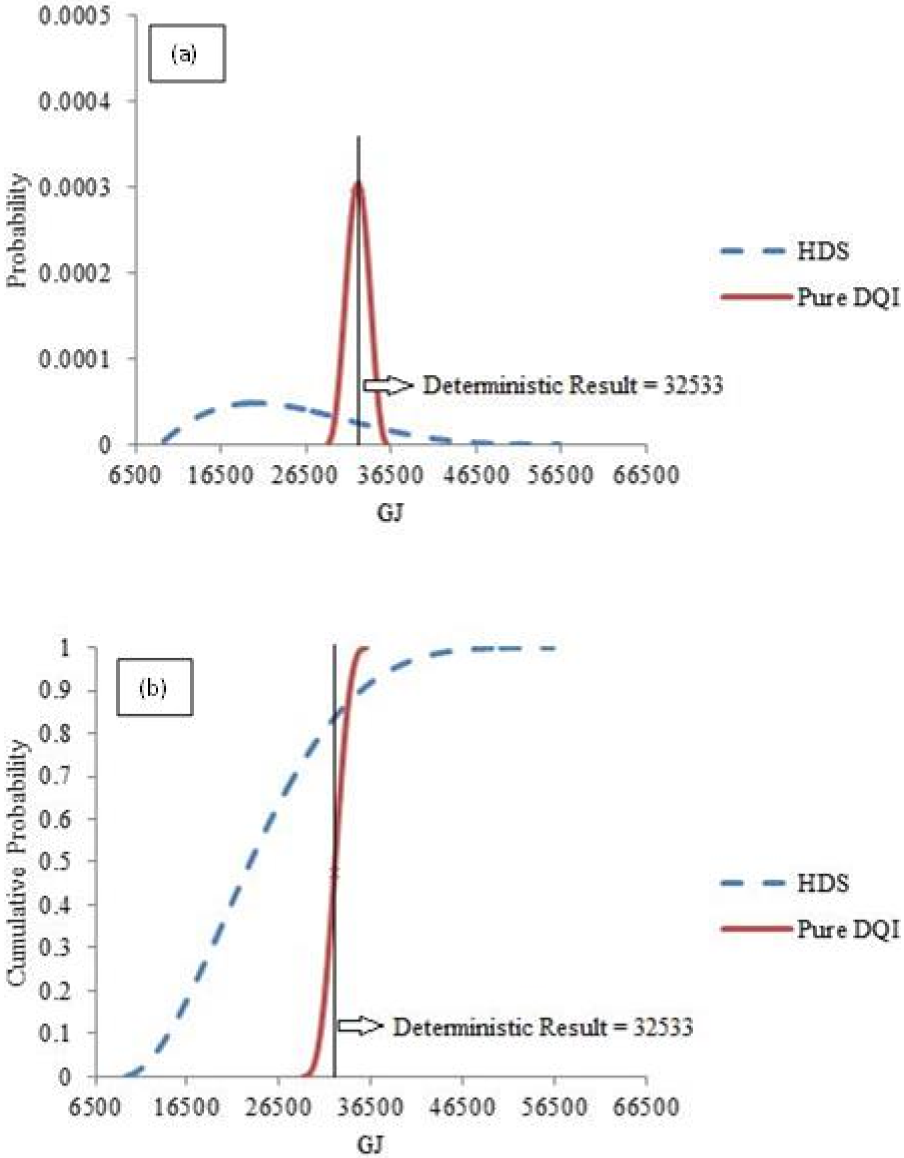


Figure 6-11. (a) TIO 4 Embodied Energy PDF results; (b) TIO 4 Embodied Energy CDF results

6.1.4 Comparison of Statistical and HDS Methods in terms of Data Requirements

It can be seen that from the procedure of the HDS approach which categorizes critical parameters and uses the statistical method to estimate their probability distributions, the HDS approach captures more possible outcomes compared to the DQI. According to Wang and Shen (2013), the statistical method requires at least 30 data points to estimate one parameter distribution. Hence in this study, 46 parameter distributions are required to be estimated for each case study with the exception of TIO 1 which has 48 parameter distributions for estimation. If the statistical method was implemented, at least 1380 data points would have been required for the estimation for each case study. That would mean 6900 data points across all the case studies. This would have been very time consuming even if all the data points were available. The HDS requires only 120 data points for each case study (600 data points across all the case studies) thus reducing the data requirements by approximately 91%. This avoids the issue associated with lack of data, and saves cost and time without seriously compromising the reliability of the HDS results as the critical parameters identified explain the majority (at least 69%) of the overall uncertainty across all the case studies.

6.1.5 Discussion

The HDS approach is used to provide insight into potential technological advancements for a 1.5 MW wind turbine and makes evident how variability of input parameters culminates in differing embodied energy and embodied carbon results. Analysing the parameter categorization revealed that EF's and EEC's for Steel, Normal concrete, Steel (no alloy), CFRP and Cast iron accounted for the majority of output uncertainty in embodied energy and embodied carbon results. Steel is the main material component of the baseline wind turbine, followed by normal concrete. The large contribution of steel is probably attributed to the wide EF and EEC distributions assigned to steel in the probability distribution estimations. Therefore any uncertainty in steel EF's and EEC's is magnified by the sheer mass of steel. Interestingly although the mass of concrete (575 tons) is greater than the mass of steel (144 tons), steel EF's and EEC's contribute more to the overall uncertainty of embodied energy and embodied carbon. For example, the EF's of steel ranges from 0.01 – 5.93 tonCO_2/ton steel, whereas values for concrete range from 0.02 – 0.28 tonCO_2/ton. Likewise, the EEC's for steel range from 8.6 – 51 GJ/ton steel, whereas values for steel (no alloy) range from 8.3 – 50.7 GJ/ton. Concrete generally is much less emission intensive than steel for CO_2 and hence, is a lesser contributor to the sensitivity of embodied carbon. It can also be observed that while normal concrete EF and steel (no alloy) EEC contribute 9% each, steel EF and steel EEC contribute 78% and 62% respectively to the resulting uncertainty. This highlights the influence of the wider distribution range of steel (no alloy) EEC compared to normal concrete EF. Due to the wide distribution ranges and mass of steel, variations in steel EF's and EEC's have significantly more impact on the embodied energy and embodied carbon uncertainty even though there is normally more concrete than steel.

For TIO 1, normal concrete and steel are also major material components of the turbine with 575 tons and 141 tons respectively. However CFRP contributes considerably to the resulting uncertainty, second only to steel, while having a mass of 8.6 tons (1% of the turbine mass). This can be attributed to CFRP being very emission and energy intensive. The EF's for CFRP range from 11.2 – 86.3 tonCO_2/ton CFRP, compared to the steel EF range of 0.01 – 5.93 tonCO_2/ton steel. Similarly, the EEC's for CFRP range from 55 – 594 GJ/ton CFRP compared to the steel EEC range of 8.6 – 51 GJ/ton steel. Hence due to the wide distribution ranges in CFRP EF and EEC input factors, despite its minor mass contribution, CFRP has a considerable impact on the uncertainty of the embodied energy and embodied carbon. For TIO 2, the major material components are normal concrete and CFRP with 575 tons and 88.5 tons respectively. Despite being second in mass to steel, CFRP contributes 99% and 97% of the resulting uncertainty for embodied carbon and embodied energy respectively. This is attributed to its high emission intensity, energy intensity and wide distribution ranges. As a result, CFRP significantly impacts the uncertainty of the embodied energy and embodied carbon.

Normal concrete and steel are the major material components in TIO 3 with 575 and 144 tons respectively. The contribution of steel to the final resulting uncertainty is again attributed to the range of values of EF's and EEC's. Cast iron has a mass of 21 tons and EEC values ranging between 11.7 – 94.5 GJ/ton which could explain the lesser contribution of steel EEC to the resulting uncertainty for the embodied energy (66%) compared to the steel EF contribution for embodied carbon (81%). For TIO 4, the major material components are normal concrete with 575 tons and CFRP with 97 tons. CFRP contributes 98% and 97% of the resulting uncertainty for embodied carbon and embodied energy respectively. Again the sheer tonnage of CFRP combined with its high emission and energy intensity, and wide distribution ranges results in its significant contribution to the resulting uncertainty of the embodied energy and embodied carbon.

The intention of quantifying uncertainty with the HDS approach in this study is to provide more information for the decision making process. From the above case studies, it is assumed that the deterministic result is used for design scheme selection aiming to find an embodied carbon and embodied energy saving design. The baseline turbine is commercially available hence in terms of embodied carbon, there is an about 85% probability (Fig. 6-2b) Enercon saved carbon emissions with the design. Thus, it is a good design in terms of embodied carbon savings. In terms of embodied energy there is a 50% probability (Fig. 6-3b) Enercon reduced the primary energy consumed during manufacture with the design. The TIO's proposed in this study are design concepts. Hence for TIO 1 in terms of embodied carbon, there is an about 15% probability (Fig. 6-4b) that a manufacturer will be able to reduce carbon emissions with this design. Hence, it is not a good design for embodied carbon savings. In terms of embodied energy, there will be a 60% (Fig. 6-5b) probability that a manufacturer will be able to reduce the primary energy consumed. This design thus performs better in terms of embodied energy savings.

For TIO 2 results show that for embodied carbon, there is a 1% probability (Fig. 6-6b) a manufacturer will be able to reduce carbon emissions therefore making it a bad design. The embodied energy results show that there is about an 85% probability (Fig. 6-7b) a manufacturer will be able to reduce the primary energy consumed making it a good design in terms of embodied energy savings. The huge difference in the results, despite CFRP's contribution of 99% and 97% to the resulting uncertainty for embodied carbon and embodied energy, can be attributed to the differences in distribution ranges of steel (no alloy) and normal concrete EEC and EF input factors. EEC values of steel (no alloy) range from 8 – 51 GJ/ton compared to EF values of concrete that range from 0.02 – 0.28 tonCO_2/ton. This highlights how variations in EF and EEC values significantly affect results of embodied carbon and embodied energy LCA.

Results show that for TIO 3 there will be an about 85% probability (Fig. 6-8b) that a manufacturer will be able to reduce carbon emissions with this design. It is therefore a good design in terms of embodied carbon savings. For embodied energy, results show that there is about a 35% probability (Fig. 6-9b) a manufacturer will be able to reduce the primary energy consumed. This design therefore performs better in terms of embodied carbon savings. For TIO 4 in terms of embodied carbon, there would be about a 1% probability (Fig. 6-10b) that a manufacturer will be able to reduce carbon emissions making it a bad design. For embodied energy, results show the probability that a manufacturer will be able to reduce the primary energy consumed is about 85% (Fig. 6-11b) making it a good design in terms of embodied energy savings. The difference in the results, despite CFRP's contribution of 98% and 97% to the resulting uncertainty for embodied carbon and embodied energy, could again be attributed to reasons described in TIO 2.

From the results of the different case studies, more information was gained for decision making using the HDS approach compared to the DQI. The confidence level which is the important factor for decision making was observed and it can be seen that the DQI approach gave more conservative results, consistent with conclusions in Venkatesh et al. (2010), Tan et al. (2002) and Lloyd and Ries (2007), which could lead to unreliable decisions. For example, the results for all the case studies showed the pure DQI approach giving a 50% probability making any decisions made using the pure DQI quite unreliable. Thus the HDS approach is a useful alternative for the evaluation of deterministic wind turbine embodied energy and embodied carbon LCA results when knowledge of the data uncertainties is required. The baseline wind turbine therefore performs best in terms of an embodied energy and embodied carbon saving scheme.

6.1.6 Section Conclusion

In this section the competence of the HDS method in estimating data uncertainty in deterministic embodied carbon and embodied energy LCA results and its application to decision making is examined through case studies. In order to evaluate the reliability of the HDS method, first, embodied carbon and embodied energy results were estimated deterministically. Then for each case study, using DQI and HDS methods, the effect on uncertainty estimates for embodied energy and embodied carbon are investigated. In performing the uncertainty analysis, the reliability measures MRE and CV are considered. Using the results obtained the following conclusions are drawn.

Firstly, with respect to the use of both methods, the HDS approach demonstrated its effectiveness in evaluating deterministic 1.5 MW wind turbine embodied carbon and embodied energy results. MRE and CV results show the HDS far outperforms the DQI. In other words, a strong argument could be made to advocate for the use of the HDS over DQI when accuracy of the uncertainty estimate is paramount.

Secondly, for the class of the problem at hand, similar conclusions can be drawn in terms of embodied energy and embodied carbon for all case studies. Uncertainty in the results largely depends on distribution ranges of the input parameters. This is magnified by the mass of the materials which result in the overall contributions to the uncertainty. Hence, it is shown that a strong relationship exists between material mass and input parameter distribution ranges.

Finally, when comparing the different turbine designs based on the studied cases, the results were quite clear. With the performance improvements incorporated using the TIO's, the baseline turbine had the best embodied carbon and embodied energy performance.

Therefore, when all the criteria are considered, the potential investor must decide whether the environmental benefits for a particular design are worth the investment.

6.2 Life Cycle Impact Assessment

This section addresses the environmental aspect of the sustainability assessment using the different wind turbine design variations in the wind farm model. There are different impact assessment methods principally based on the problem oriented (mid-point) and damage oriented (end-point) impact categories. All environmental indicators have been estimated using the Centre of Environmental Science of Leiden University CML 2001 impact assessment methodology (Guinée, 2002) which focuses on midpoints of the cause-effect chain, and potential environmental impact categories were selected according to the aims of the work. The LCA software SimaPro (PRé Consultants, 2012) and the Ecoinvent v2.2 database (Dones et al., 2007) have been used for these purposes. All estimates are based on the modelling carried out in this study. Contributions to impacts of the different design variations are presented and discussed in the following sections. Full results of the total impacts and contribution analysis of the life cycle stages can be found in Tables 6-5 and 6-6.

Table 6-5. Life cycle environmental impacts per kWh of the wind farm using the different turbine design variations (ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; GWP: Global Warming Potential; ODP: Ozone Depletion Potential; HTP: Human Toxicity Potential; FAETP: Fresh water Aquatic Eco-toxicity Potential; MAETP: Marine Aquatic Eco-toxicity Potential; TETP: Terrestrial Eco-toxicity Potential; POP: Photochemical Ozone Creation Potential).

Impact Categories (unit)	**Baseline Turbine**	**TIO 1**	**TIO 2**	**TIO 3**	**TIO 4**
ADP (kg Sb) eq.	8.9E-05	9.49E-05	1.26E-04	7.98E-05	1.22E-04
AP (kg SO_2) eq.	9.17E-05	9.39E-05	1.06E-04	5.89E-05	7.74E-05
EP (kg PO_4) eq.	6.9E-05	6.91E-05	6.46E-05	3.69E-05	3.42E-05
GWP (kg CO_2) eq.	1.18E-02	1.25E-02	1.66E-02	1.03E-02	1.59E-02
ODP (kg CFC) eq.	1.24E-09	1.23E-09	9.18E-10	1.11E-09	7.86E-10
HTP (kg 1,4DB) eq.	5.38E-02	5.35E-02	5.08E-02	2.51E-02	2.31E-02
FAETP (kg 1,4-DB) eq.	1.95E-02	1.95E-02	1.66E-02	1.04E-02	8E-03
MAETP (kg 1,4-DB) eq.	44.8	44.7	40	21.1	17.3
TETP (kg 1,4-DB) eq.	2.24E-04	2.2E-04	1.6E-04	1.51E-04	8.7E-05
POP (kg C_2H_4) eq.	6.54E-06	6.62E-06	5.9E-06	4.95E-06	4.5E-06

Table 6-6. Percentage contribution of the different stages to the life cycle impacts of the farm

Impact Categories (%)	**Life cycle stage**	**Baseline Turbine**	**TIO 1**	**TIO 2**	**TIO 3**	**TIO 4**
ADP	Construction	89.1	89.8	93	92.2	95.6
	Operation	6.13	5.75	4.13	2.75	1.69
	Decommissioning	4.76	4.49	2.84	5	2.74
AP	Construction	83.6	84	87	93.4	95.7
	Operation	12.9	12.6	10.6	1.64	1.19
	Decommissioning	3.47	3.4	2.44	4.98	3.1
EP	Construction	82.8	82.9	82.6	97	97.1
	Operation	16.3	16.2	16.6	1.4	1.45
	Decommissioning	0.91	0.91	0.83	1.6	1.47
GWP	Construction	88.6	89.2	92.6	92.1	95.5
	Operation	6.79	6.42	4.61	2.91	1.8
	Decommissioning	4.61	4.38	2.77	4.98	2.73
ODP	Construction	60.6	60	58.6	62.8	60.1
	Operation	3.53	3.57	4.56	1.32	1.78
	Decommissioning	35.8	36.4	36.9	35.9	38.1
HTP	Construction	81.6	81.5	81.5	98.8	98.9
	Operation	18	18.1	18.2	0.35	0.36
	Decommissioning	0.42	0.42	0.36	0.83	0.74
FAETP	Construction	83.4	83.4	81.5	98	97.7
	Operation	16.2	16.2	18.2	1.29	1.59
	Decommissioning	0.35	0.35	0.36	0.63	0.72
MAETP	Construction	81.5	81.5	80.3	98.2	98
	Operation	18.1	18.1	19.3	0.9	1.1
	Decommissioning	0.42	0.42	0.41	0.85	0.91
TETP	Construction	88.5	88.3	84.7	99.1	98.7
	Operation	11	11.2	14.7	0.2	0.34
	Decommissioning	0.53	0.54	0.6	0.7	1
POP	Construction	87.2	87.4	87.1	94.1	94.5
	Operation	9.43	9.31	9.99	1.9	2
	Decommissioning	3.35	3.33	2.94	4	3.5

6.2.1 Interpretation of Results

The following section gives an overview of the main contributors to each environmental impact category.

Abiotic Depletion Potential (ADP): The lowest ADP value observed is 7.98E-05 kg Sb eq./kWh for TIO 3 and the highest observed ADP value is 1.26E-04 kg Sb eq./kWh for TIO 2. The construction stage has the largest contribution to ADP for all the turbine designs with 89.1%, 89.8%, 93%, 92.2% and 95.6% for the baseline turbine and TIOs 1 – 4 respectively. The operation stage has the second largest contribution to ADP for the baseline turbine, TIO 1 and TIO 2 with 6.13%, 5.75% and 4.13% respectively. The decommissioning stage has the least contribution to ADP for the baseline turbine, TIO 1 and TIO 2 with 4.76%, 4.49% and 2.84%. For TIOs 3 and 4, the decommissioning stage has the second largest contribution to ADP while the operation stage has the least contribution. This impact mainly relates to the depletion of energy used (in the form of coal, natural gas and crude oil) in glass-reinforced nylon production as well as production of high-alloy steels in the nacelle, generator and grid connection.

Acidification Potential (AP): The minimum AP value obtained is 5.89E-05 kg SO_2 eq./kWh for TIO 3 and the maximum observed AP value is 1.06E-04 kg SO_2 eq./kWh for TIO 2. The construction stage is the largest contributor to AP for the baseline turbine and TIOs 1 – 4 with 83.6%, 84%, 87%, 93.4% and 95.7% respectively. The operation stage has the second largest contribution to AP for the baseline turbine, TIO 1 and TIO 2 with 12.9%, 12.6% and 10.6% respectively. For TIOs 3 and 4, the operation stage has the least contribution to AP with 1.64% and 1.19%. For the baseline turbine, TIO 1 and TIO 2, the decommissioning stage has the least contribution to AP with 3.47%, 3.4% and 2.44% respectively. The decommissioning stage is the second largest contributor to AP for TIO 3 and TIO 4 with 4.98% and 3.1%. This impact primarily relates to production of the tower and foundations. The emissions to air of nitrogen oxides and sulphur dioxide associated with the production of iron, steel and glass-reinforced nylon are the primary contributing substances.

Eutrophication Potential (EP): The lowest EP value observed is 3.42E-05 kg PO_4 eq./kWh for TIO 4 and the highest observed EP value is 6.91E-05 kg PO_4 eq./kWh for TIO 1. The construction stage has the largest contribution to EP for all the turbine designs with 82.8%, 82.9%, 82.6%, 97% and 97.1% for the baseline turbine and TIOs 1 – 4 respectively. The operation stage has the second largest contribution to EP for the baseline turbine, TIO 1 and TIO 2 with 16.3%, 16.2% and 16.6%. The decommissioning stage has the least contribution to EP for the baseline turbine, TIO 1 and TIO 2 with 0.912%, 0.91% and 0.83% respectively. For TIOs 3 and 4, the decommissioning stage has the second largest contribution to EP while the operation stage has the least contribution. The main turbine components contributing to EP are tower and foundation. The primary substances contributing to EP are the emissions to air and water of nitrogen oxides and phosphate.

Global Warming Potential (GWP): The minimum GWP value obtained is 1.03E-02 kg CO_2 eq./kWh for TIO 3 and the maximum observed GWP value is 1.66E-02 kg CO_2 eq./kWh for TIO 2. The construction stage is the largest contributor to GWP for the baseline turbine and TIOs 1 – 4 with 88.6%, 89.2%, 92.6%, 92.1% and 95.5%. The operation stage has the second largest contribution to GWP for the baseline turbine, TIO 1 and TIO 2 with 6.79%, 6.42% and 4.61%. For TIOs 3 and 4, the operation stage has the least contribution to GWP with 2.91% and 1.8%. For the baseline turbine, TIO 1 and TIO 2, the decommissioning stage has the least contribution to GWP with 4.61%, 4.38% and 2.77% respectively. The decommissioning stage is the second largest contributor to GWP for TIO 3 and TIO 4 with 4.98% and 2.73%. The tower is the main contributing component to GWP. The emissions to air of carbon dioxide and methane are the main contributing substances which result from fuel combustion largely during production of steel and glass-reinforced nylon for the turbine.

Ozone Depletion Potential (ODP): The lowest ODP value observed is 7.86E-10 kg CFC-11eq./kWh for TIO 4 and the highest observed ODP value is 1.24E-09 kg CFC-11eq./kWh for the baseline turbine. The construction stage has the largest contribution to ODP for all the turbine designs with 60.6%, 60%, 58.6%, 62.8% and 60.1% for the baseline turbine and TIOs 1 – 4 respectively. The decommissioning stage has the second largest contribution to ODP for the baseline turbine and TIOs 1 – 4 with 35.8%, 36.4%, 36.9%, 35.9% and 38.1% respectively. The operation stage has the least contribution to ODP for all the turbine designs with 3.53%, 3.57%, 4.56%, 1.32% and 1.78%. Emissions of non-methane volatile organic compound (NMVOCs) i.e. halons 1001, 1211 and 1301 during production of fiberglass, steel, concrete and transportation of components are the major contributors to this impact.

Human Toxicity Potential (HTP): The minimum HTP value obtained is 2.31E-02 kg 1,4-DB eq./kWh for TIO 4 and the maximum observed HTP value is 5.38E-02 kg 1,4-

DB eq./kWh for the baseline turbine. The construction stage is the largest contributor to HTP for the baseline turbine and TIOs 1 – 4 with 81.6%, 81.5%, 81.5%, 98.8% and 98.9% respectively. The operation stage has the second largest contribution to HTP for the baseline turbine, TIO 1 and TIO 2 with 18%, 18.1% and 18.2%. For TIOs 3 and 4, the operation stage has the least contribution to HTP with 0.35% and 0.36%. For the baseline turbine, TIO 1 and TIO 2, the decommissioning stage has the least contribution to HTP with 0.42%, 0.42% and 0.36% respectively. The decommissioning stage is the second largest contributor to HTP for TIO 3 and TIO 4 with 0.83% and 0.74%. The main contributing substances to HTP are the release to air and water of heavy metals such as antimony and arsenic which result from the production of stainless steel materials.

Freshwater Aquatic Eco-toxicity Potential (FAETP): The lowest FAETP value observed is 8.00E-03 kg 1,4-DB eq./kWh for TIO 4 and the highest observed FAETP value is 1.95E-02 kg 1,4-DB eq./kWh for the baseline turbine and TIO 1. The construction stage has the largest contribution to FAETP for all the turbine designs with 83.4%, 83.4%, 81.5%, 98% and 97.7% for the baseline turbine and TIOs 1 – 4 respectively. The operation stage has the second largest contribution to FAETP for the baseline turbine and TIOs 1 – 4 with 16.2%, 16.2%, 18.2%, 1.29% and 1.59% respectively. The decommissioning stage has the least contribution to FAETP for all the turbine designs with 0.35%, 0.35%, 0.36%, 0.63% and 0.72%. The production of polymer materials (polyethylene and PVC) resulting in the emission of benzo(a)pyrene to fresh water is the major contributor to this impact. Other contributing substances are related to the release of heavy metals to water such as copper, zinc, beryllium and nickel. These heavy metal releases are as a result of metal production processes used for the turbines.

Marine Aquatic Eco-toxicity Potential (MAETP): The minimum MAETP value obtained is 17.3 kg 1,4-DB eq./kWh for TIO 4 and the maximum observed MAETP value is 44.8 kg 1,4-DB eq./kWh for the baseline turbine. The construction stage is the largest contributor to MAETP for the baseline turbine and TIOs 1 – 4 with 81.5%, 81.5%, 80.3%, 98.2% and 98% respectively. The operation stage has the second largest contribution to MAETP for the baseline turbine and TIOs 1 – 4 with 18.1%, 18.1%, 19.3%, 0.9% and 1.1% respectively. The decommissioning stage has the least contribution to MAETP for all the turbine designs with 0.42%, 0.42%, 0.41%, 0.85% and 0.91%. The impacts towards MAETP are primarily due to emissions of heavy metals to air and water which result, for example, from the production of stainless steel materials.

Terrestrial Eco-toxicity Potential (TETP): The lowest TETP value observed is 8.70E-05 kg 1,4-DB eq./kWh for TIO 4 and the highest observed TETP value is 2.24E-04 kg 1,4-DB eq./kWh for the baseline turbine. The construction stage has the largest contribution to TETP for all the turbine designs with 88.5%, 88.3%, 84.7%, 99.1% and 98.7% for the baseline turbine and TIOs 1 – 4 respectively. The operation stage has the second largest contribution to TETP for the baseline turbine, TIO 1 and TIO 2 with 11%, 11.2% and 14.7%. For TIOs 3 and 4, the operation stage has the least contribution to TETP with 0.2% and 0.34%. For the baseline turbine, TIO 1 and TIO 2, the decommissioning stage has the least contribution to TETP with 0.53%, 0.54% and 0.6% respectively. The decommissioning stage is the second largest contributor to TETP for TIO 3 and TIO 4 with 0.7% and 1%. The impacts towards TETP are primarily driven by the release of heavy metals to air, soil and water relating mainly to arsenic, mercury and chromium. These emissions are as a result of the production of metals used in the turbine, mainly steel and stainless steels.

Photochemical Ozone Creation Potential (POP): The minimum POP value obtained is 4.50E-06 kg C_2H_4 eq./kWh for TIO 4 and the maximum observed POP value is 6.62E-06 kg C_2H_4 eq./kWh for TIO 1. The construction stage is the largest contributor to POP for the baseline turbine and TIOs 1 – 4 with 87.2%, 87.4%, 87.1%, 94.1% and 94.5% respectively. The operation stage has the second largest contribution to POP for the baseline turbine, TIO 1 and TIO 2 with 9.43%, 9.31% and 9.99% respectively. For TIOs 3 and 4, the operation stage has the least contribution to POP with 1.9% and 2%. For the baseline turbine, TIO 1 and TIO 2, the decommissioning stage has the least contribution to POP with 3.35%, 3.33% and 2.94% respectively. The decommissioning stage is the second largest contributor to POP for TIO 3 and TIO 4 with 4% and 3.5%. The main contributing substances to this impact are carbon monoxide, benzene, butane and ethane from aluminium and steel production processes.

6.2.2 Discussion

6.2.2.1 Construction Stage

According to the contribution analysis of the different life cycle stages to the life cycle impacts of the wind farm, the construction stage is the major contributor to the life cycle impacts across all the studied cases. The environmental impacts of the construction stage for the baseline turbine are compared to that of TIOs 1 - 4. Figure 6-12 shows the characterized impact assessment results of the comparison. As shown four of the impacts from the baseline turbine, ODP, HTP, MAETP and TETP, are higher than for TIOs 1 - 4, ranging from 0.4% higher MAETP for TIO 1 to 56.8% higher TETP for TIO 4. This is largely due to the emissions from steel and copper production for the generators, towers and grid connections. The exceptions to this are ADP, AP, GWP, EP, FAETP and POP which range from 0.1% to 32.3% lower for the baseline turbine. The results also suggest that in the construction stage, the baseline turbine is less environmentally sustainable than TIOs 1 – 4 for four out of ten environmental categories. The impacts with the highest contributions for TIO 1 are EP, FAETP and POP ranging from 0.1% to 1.4% higher than for the baseline turbine. The remaining seven environmental impacts range from 0.4% to 2.4% lower for TIO 1. Despite the 30% increase in blade mass which incorporates the use of glass-reinforced nylon, the higher contributions of EP, FAETP and POP could again be attributed to steel and copper production for the generators, towers and grid connections. TIO 1 is therefore less environmentally sustainable for three environmental categories compared to the baseline turbine in the construction stage.

For TIO 2, the impacts with the highest contributions are ADP, AP and GWP ranging from 17.1% to 32.2% higher than for the baseline turbine. This can be attributed to the production of glass-reinforced nylon (a highly energy and emission intensive material), steel and copper. Glass-reinforced nylon contributes 94% to the material composition of the tower compared to its 40% blade composition in TIO 1. The higher contributions of ADP, AP and GWP are therefore due to the high energy and emission intensity of glass-reinforced nylon as well as the large tower mass (93,941 kg). The other impacts EP, ODP, HTP, FAETP, MAETP, TETP and POP range from 5.8% to 31.8% lower for TIO 2. It can thus be said that in the construction stage, TIO 2 is less environmentally sustainable than the baseline turbine for three environmental categories.

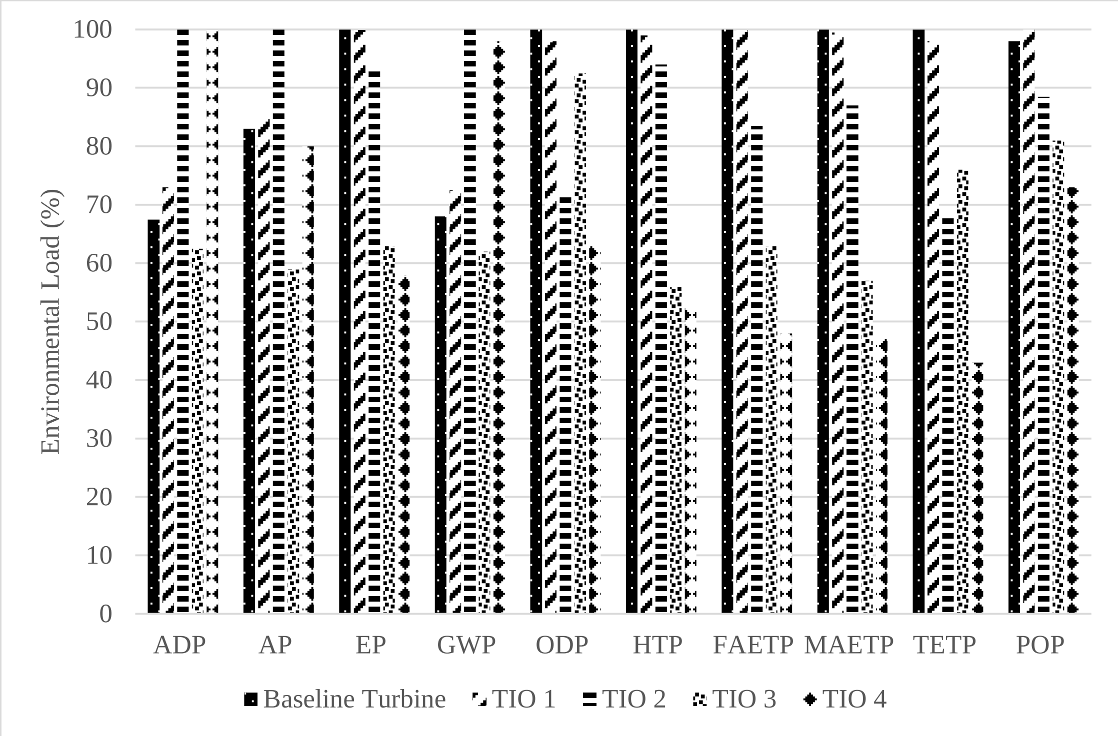


Figure 6-12. Characterization results for the comparison between the construction stages of the baseline turbine and TIOs 1 - 4

ODP, POP and TETP are the impacts with the highest contributions for TIO 3. However, none of these impacts are higher than for the baseline turbine but instead range from 7.8% to 31.8% lower. The reason for this is the 78% reduction in generator mass as a result of iron use in the rotors instead of copper. Iron is a less energy intensive material compared to copper resulting in a decrease in the environmental implications across all of the impact categories. Therefore in the construction stage, TIO 3 is more environmentally sustainable than the baseline turbine for all of the environmental categories. For TIO 4, ADP and GWP are the impacts with the highest contributions and are 30.4% and 32.2% higher respectively compared to the baseline turbine. The reason for this could be attributed to the production of glass-reinforced nylon as a result of its use in the blade and tower. The environmental impact from glass-reinforced nylon, though a significant contributor to ADP and GWP, is offset in the remaining environmental categories by the lower environmental footprint of iron due to the reduced generator mass. As a result, TIO 4 is less environmentally sustainable than the baseline turbine for two environmental categories in the construction stage. Appendix B: Figure B-1 shows the normalized results for the construction stage. It indicates that the impact towards MAETP from all the designs is by far the most significant. This is followed by the impact towards FAETP from all the designs.

6.2.2.2 Operation Stage

The operation stage was the second largest contributor to the life cycle impacts across most of the studied cases. Figure 6-13 shows the characterized impact assessment results of the comparison. As shown, all of the contributions to impacts from the baseline turbine and TIO 1 are higher compared to contributions from TIOs 2, 3 and 4. The similar contributions of the baseline turbine and TIO 1 across all the environmental categories can be attributed to the similar inputs as regards the material masses used for the generator replacements as well as transportation and energy related processes. For the most part, majority of the impacts from both designs are due to the production of copper and steel used for manufacture of the generators during renewal of half of the generators in the operational life of the wind farm. The baseline turbine and TIO 1 are therefore the least environmentally sustainable designs in the operation stage.

For TIO 2, similar contributions of 95.5% can be observed across all the environmental categories. Despite similar inputs for the generator replacements, energy and transportation processes with the baseline turbine and TIO 1, there is a 4.5% reduction in the results for all the environmental categories. This can be attributed to the influence of capacity factor on environmental impact assessment results. According to Weinzettel et al. (2009), Demir and Taşkin (2013) and Greening and Azapagic (2013), the environmental impact for one functional unit decreases with a higher capacity factor because the energy output is directly related to the environmental sustainability of a wind turbine. Hence, the difference in the contribution of TIO 2 to the environmental categories compared to the baseline turbine and TIO 1 can be attributed to the 22% capacity factor calculated for the wind farm using TIO 2 compared to 21% for the wind farm using the baseline turbine and TIO 1. Majority of the impacts for TIO 2 are attributed to copper and steel production as explained for the baseline turbine and TIO 1. It can hence be said that TIO 2 is more environmentally sustainable than the baseline turbine and TIO 1 in the operation stage.

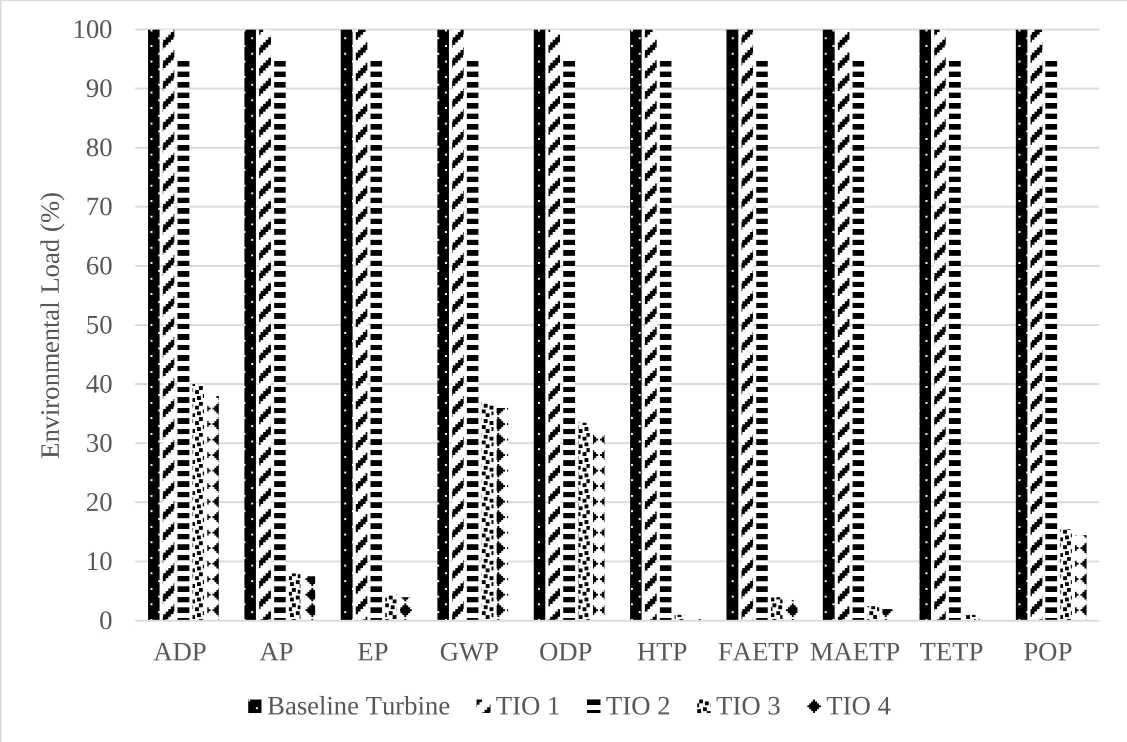


Figure 6-13. Characterization results for the comparison between the operation stages of the baseline turbine and TIOs 1 - 4

As shown, all the contributions to impacts for TIO 3 are lower than contributions from the baseline turbine, TIO 1 and TIO 2 ranging from 60% to 99% lower. The contributions to impacts for TIO 3 are however higher than contributions for TIO 4 across all the environmental categories ranging from 0.05% to 1.8% higher. This is despite having the same energy, transport and generator material inputs with TIO 4. The generators used for modelling component replacement in TIOs 3 and 4 have a 78% reduced mass due to iron use in the rotors instead of copper as highlighted in the construction stage. This explains the disparity in results for the contributions to impacts of TIO 3 and TIO 4 as compared to the baseline turbine, TIO 1 and TIO 2. The differences in the contributions to impacts for TIO 3 and TIO 4 can again be attributed to the capacity factors calculated for the wind farm using both turbine designs. The capacity factors calculated for TIOs 3 and 4 are 21% and 22% respectively explaining the lower contributions of TIO 4 compared to TIO 3 for all the environmental categories. Majority of the impacts from both designs are due to the production of steel and electricity mix used during manufacture of the generators. TIO 4 can therefore be said to be the most environmentally sustainable design in the operation stage. Appendix B: Figure B-2 shows the normalized results for the operation stage. It indicates that the impact towards MAETP from the baseline turbine, TIO 1 and TIO 2 is by far the most significant. This is followed by the impact towards FAETP from the baseline turbine, TIO 1 and TIO 2.

6.2.2.3 Decommissioning Stage

The decommissioning stage was the lowest contributor to the life cycle impacts across most of the studied cases. Characterized impact assessment results of the comparison are shown in Figure 6-14. For the baseline turbine, none of its contributions to the environmental categories are higher than contributions from TIO 1 (which has the highest for all the environmental categories). The impacts range from 0.2% to 0.6% lower for the baseline turbine. The reason for this is the larger mass per wind farm of TIO 1 compared to the baseline turbine. The material composition of the baseline turbine amounts to a total mass per wind farm of 21,987 tons compared to 22,116 tons for TIO 1. It can thus be said that TIO 1 is the least environmentally sustainable design in the decommissioning stage. TIO 2 has lower contributions for all the environmental categories compared to the baseline turbine and TIO 1. These contributions range from 11.8% to 24.3% lower for TIO 2. This can be attributed to the lower mass of TIO 2 (17,480 tons per wind farm due to the tower mass reduction of 38%) compared to 21,987 tons and 22,116 tons for the baseline turbine and TIO 1 respectively. TIO 2 is therefore more environmentally sustainable than the baseline turbine and TIO 1 in the decommissioning stage.

All contributions to the environmental categories for TIO 3 are lower than contributions from the baseline turbine and TIO 1 ranging from 4.2% to 11.4% lower. The reason for the lower contributions is the 19,570 ton mass per wind farm due to the generator mass reduction described in the construction stage. TIO 3 can hence be said to be more environmentally sustainable than the baseline turbine and TIO 1, but less environmentally sustainable compared to TIO 2. TIO 4 has the least contributions towards all the environmental categories compared to the other designs ranging from 15% to 33% lower. This can be attributed to TIO 4 having the smallest mass per wind farm (15,428 tons) compared to the other turbine designs. TIO 4 is therefore the most environmentally sustainable design for all the environmental categories in the decommissioning stage. The causes of the impacts across all the studied cases are largely due to the electricity mix used during the dismantling of components, component transportation and crane use during the disassembly process. Normalized results for the decommissioning stage are given in in Appendix B: Figure B-3. The impact towards MAETP from all the designs is seen to be by far the most significant. This is followed by the impact towards FAETP from all the designs.

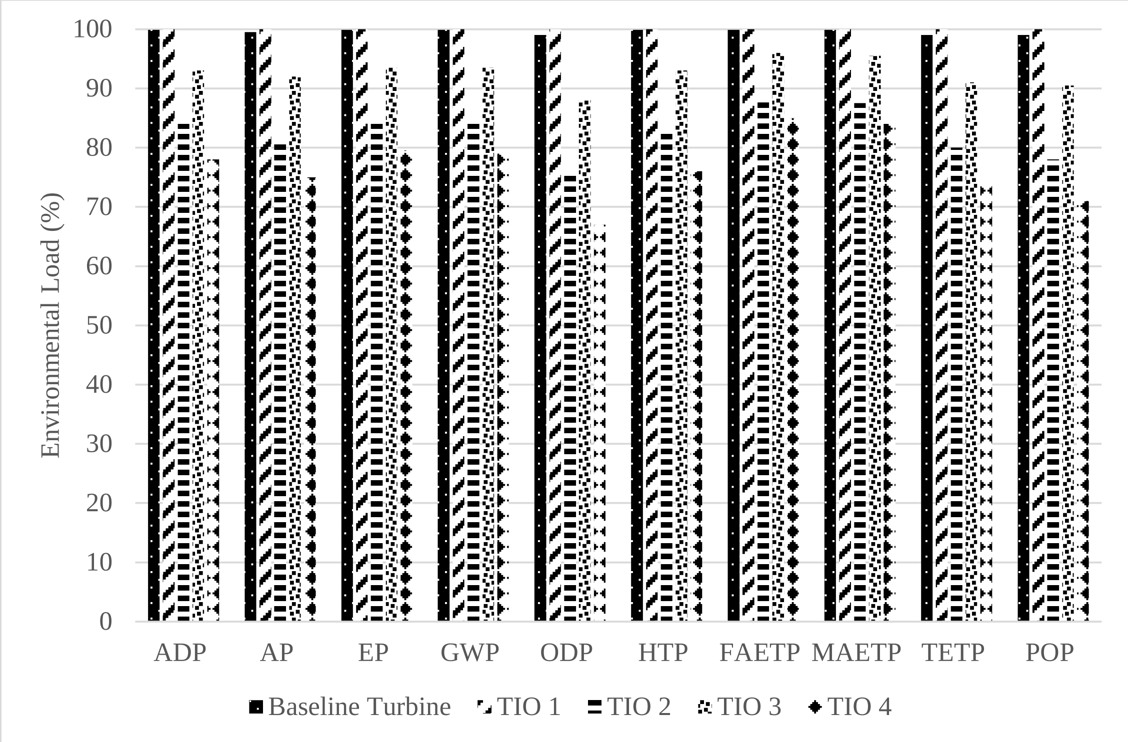


Figure 6-14. Characterization results for the comparison between the decommissioning stages of the baseline turbine and TIOs 1 - 4

6.2.2.4 Life cycle Impacts

Characterized life cycle environmental impact results of the wind farm for the baseline turbine in comparison with TIOs 1 - 4 are given in Figure 6-15. The figure shows, per environmental category, the relative contributions of all the design variations considered. In this way, differences in the contributions to environmental impacts introduced by the decision taken to offer a clearer picture of the environmental sustainability for a 1.5 MW wind turbine incorporating different technological advancements on a wind farm can be appreciated. As can be seen, the baseline turbine has higher contributions to impacts compared to TIOs 1 – 4 in the categories ODP, MAETP, HTP and TETP. It is equivalent in FAETP contributions with TIO 1, and has lower contributions to ADP – 41.6% lower than to TIO 2, AP – 15.6% lower than TIO 2, EP – 0.14% lower than TIO 1, GWP – 40.7% lower than TIO 2 and POP – 1.2% lower than TIO 1. With the incorporation of the technological advancements, the materials used in the wind turbine components and their associated masses are varied. For TIO 1, compared to the baseline turbine, the contribution to impacts increased for five environmental categories ADP – 6.6% higher, AP – 2.4% higher, EP – 0.14% higher, GWP – 5.9% higher and POP – 1.2% higher, due to its higher material mass. TIO 2 showed an increase in contributions to three environmental categories, ADP – 41.6% higher, AP – 16% higher and GWP – 40.7% higher, compared to the baseline turbine. Lower contributions to all the environmental categories were observed for TIO 3 compared to the baseline turbine, as well as increased contributions towards ADP – 37% higher, and GWP – 34.8% higher, for TIO 4 compared to the baseline turbine.

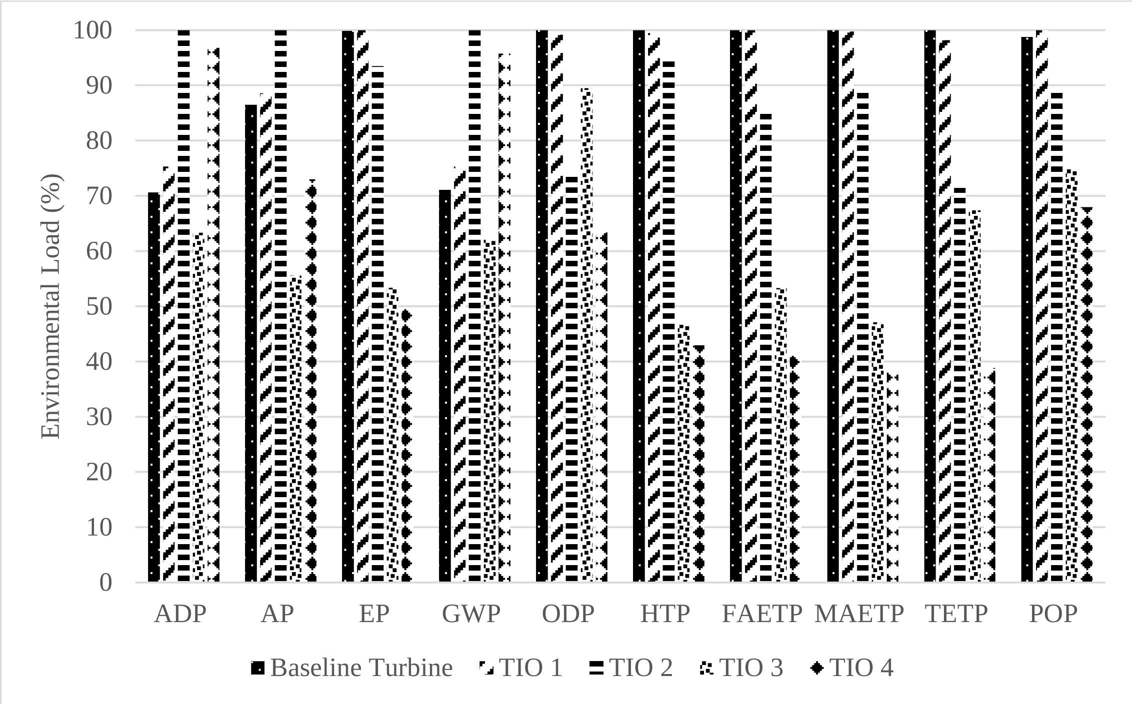


Figure 6-15. Characterization results for life cycle environmental impacts of the wind farm for the baseline turbine compared to TIOs 1 – 4

Since higher tower height generally improves access to wind resource, TIOs 2 and 4 experience higher capacity factors compared to the other designs. However, the comparison of TIOs 2 and 4 to the baseline turbine shows the disadvantage of both designs with respect to ADP and GWP. The higher capacity factors experienced by the wind farm using TIO 2 and TIO 4 did not offset the higher environmental costs as a result of the increased use of glass-reinforced nylon in both designs. However, TIOs 2 and 4 have lower contributions to the environmental categories EP, ODP, MAETP, FAETP, HTP, POP and TETP compared to the baseline turbine. The exception is AP where TIO 2 has a 13.8% higher contribution and TIO 4 has a 13.4% lower contribution compared to the baseline turbine. The main life cycle impacts of the analysed wind farm occur during the construction stage. In view of this, glass-reinforced nylon, steel and copper are the materials with the highest contributions to impacts due to their large quantity and high energy/emission intensity. Other significant contributors to impacts are caused by fibre glass and concrete (due to its sheer tonnage). Despite the high energy/emissions intensity of aluminium, impacts related to its usage are less notable because of its relatively small mass. Normalized results for the life cycle environmental impacts are given in Appendix B: Figure B-4. The impact towards MAETP from all the designs is seen to be by far the most significant. This is followed by the impact towards FAETP and HTP from all the designs.

6.2.2.5 Comparison of results with Literature

A number of wind farm LCA studies have been carried out (Vestas, 2006 - 300 MW onshore farm consisting of V82-1.65 MW turbines; PE, 2011 - 100 MW onshore farm composed of 3 MW V112 turbines; Garrett and Rønde, 2013 - 50 MW onshore farm comprising 2 MW Grid Streamer turbines; Vestas, 2013 – 90 MW onshore farm composed of V90-3.0 MW turbines; Vestas, 2014 – 100 MW onshore farm consisting of V126-3.3 MW turbines) all in western European locations. A direct comparison of the results between them is however problematic due to the different assumptions made which generally include energy outputs, capacity factors, turbine capacities and differing designs. In all of the studies, the focus has been on Vestas wind turbines with rated capacities between 1.65 MW and 3.3 MW. For these reasons, as illustrated in Figure 6-16, environmental impacts of the wind farms described in the various studies vary. For example, GWP ranges from 6.2 to 8.2 g CO_2 eq./kWh for the different capacities and designs. At between 10.3 and 16.6 g CO_2 eq./kWh, the GWPs estimated in this study for the baseline turbine and TIOs are higher than this range. As there are no studies for the 1.5 MW capacity, the closest turbine size available is 1.65 MW for which the GWP is estimated at 7.1 g CO_2 eq./kWh. Apart from the different rated capacities and designs used in the Vestas studies, the major reason for the difference in results is the fact that recycling of materials in the decommissioning stage is not considered in this study. According to Davidsson et al. (2012), the environmental impacts embodied in a wind turbine are reduced by approximately half through end-of-life recycling.

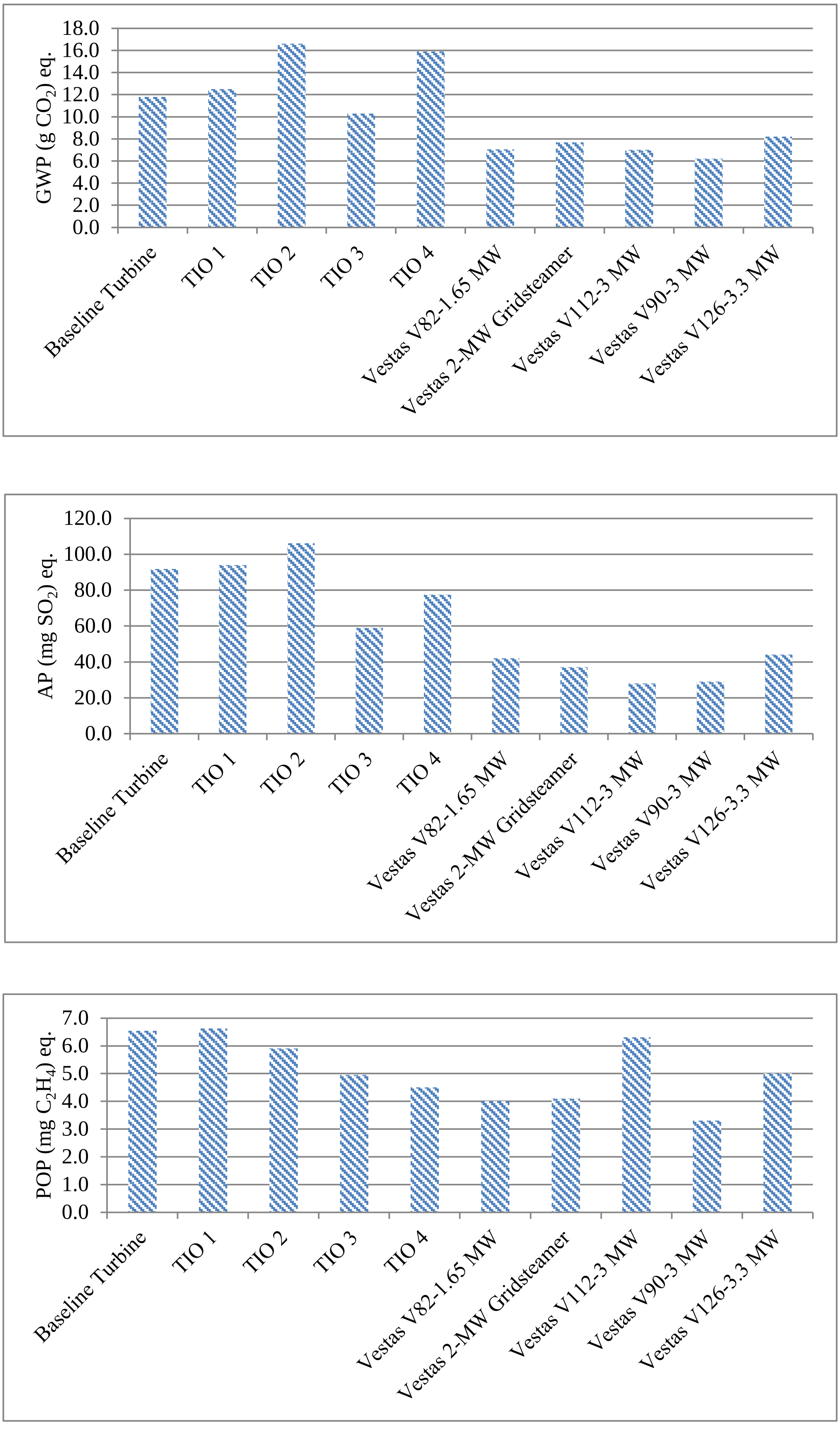


Figure 6-16. Estimated GWP, AP and POP for the wind farm using the different design variations compared with literature

This is highlighted in Tremeac and Meunier (2009) and Chen et al. (2011) where a 26 – 27% reduction in total environmental indicator values is observed. Similar differences are observed for AP, with the exception of POP, for which the Vestas V112-3 MW and V126-3.3 MW turbines have impact contributions comparable to results obtained in this study i.e. 6.3 mg C_2H_4 eq./kWh and 5 mg C_2H_4 eq./kWh respectively. This can be attributed to the higher contribution of the manufacturing stages for the V112-3 MW and V126-3.3 MW turbines towards POP compared to the other Vestas turbines. As Volatile organic compounds (VOCs) emissions from steel and aluminium production processes contribute significantly towards POP in the two studies, it suggests that Vestas factory operations within the manufacturing stage for the V112-3 MW and V126-3.3 MW turbines have a larger contribution to this impact compared to the other Vestas turbines. The comparison also suggests that there is no seeming relationship between wind turbine capacity and contribution to environmental impacts although typically, larger wind turbines have lower GWP compared to smaller scale installations. For example according to Amor et al. (2010), a 1 kW turbine generates 2314 kWh/year with a GWP of 160 g CO_2 eq./kWh. In contrast, a 4.5 MW turbine produces 1.7 GWh/year while having a GWP of 9 g CO_2 eq./kWh (Tremeac and Meunier, 2009). Therefore the findings from the wind farm modelled using the baseline turbine and TIOs 1 - 4 suggest that given end-of-life recycling was not considered in this study, the life cycle impacts compare well with the Vestas wind farm studies.

6.2.3 Section Conclusion

In this section the environmental sustainability of a 1.5 MW wind turbine incorporating different technological advancements on a wind farm is examined through case studies. In order to evaluate the environmental performance of the wind farm, first, the wind farm was modelled using the baseline turbine and TIOs 1 - 4. Then for TIOs 1 - 4, the life cycle effects on the environmental categories are investigated and compared against the baseline turbine. In performing the life cycle modelling of the wind farm using TIOs 2 and 4, the effect of improved capacity factor is considered. With the results obtained the following conclusions are drawn.

Firstly, with respect to the life cycle environmental impacts of the wind farm using the baseline turbine, four environmental categories are higher compared to TIOs 1 - 4 ranging from 0.3% higher MAETP for TIO 1 to 61.2% higher TETP for TIO 4. The result suggests that the baseline turbine is less environmentally sustainable than TIOs 1

- 4 for four out of ten environmental categories. In other words, a strong argument could be made to advocate for the use of the baseline turbine as it compares favourably with TIOs 1 – 4.

Secondly, similar conclusions can be drawn in terms of incorporation of the technological advancements. The contribution to ADP, AP, EP, GWP and POP between TIOs 1, 2 and 4 increased compared to the baseline turbine due to higher material masses as well as environmental characteristics of the materials used. TIO 3 however showed lower contributions for all the environmental categories compared to the baseline turbine. Hence, it is shown that a strong relationship exists between material mass and environmental characteristics of the materials used.

Thirdly, when comparing the life cycle environmental impacts of TIOs 2 and 4 with the baseline turbine, the results are considerably less clear. Even with the higher capacity factors experienced using both designs, the environmental impacts due to the increased use of glass-reinforced nylon were not offset for the environmental categories ADP and GWP compared to the baseline turbine.

Therefore, when all the criteria are considered, some environmental trade-offs will be required if TIOs 1 – 4 are to play a role in supplying future grid electricity.

6.3 Economic Assessment

The economic analysis presented in this section encompasses the estimation of capital and operational expenditure for the wind farm using the different turbine design variations. Additionally, the payback times for the wind farm using the different turbine designs have been estimated and compared with the data reported in literature. The results are presented and discussed below. Full results of the economic assessment can be found in Tables 6-7.

Table 6-7. Life cycle costs of the wind farm using the different turbine design variations

	Baseline turbine	**TIO 1**	**TIO 2**	**TIO 3**	**TIO 4**
Capital Investment (£)	50,795,530	59,033,512	94,130,619	43,701,834	84,938,851
Revenue (£/yr)	17,548,394	17,548,394	17,774,117	17,548,394	17,774,117
O&M (£/yr)	2,200,275	2,200,275	2,218,065	2,200,275	2,218,065
Payback time (years)	3.3	3.8	6.1	2.8	5.5

6.3.1 Capital Investment

Figure 6-17 shows the capital investment required for the wind farm using the baseline turbine and TIOs 1 – 4. As shown the capital investment for the wind farm using the baseline turbine is £50,795,530 which is 14% higher than for TIO 3. This is due to the higher cost of the direct drive generator used in the baseline turbine (£220,427) compared to the cost of the single-stage/permanent magnet generator used in TIO 3 (£55,004). Compared to the other turbine designs the capital investment of the wind farm using the baseline turbine is 16%, 85%, and 67% lower than for TIOs 1, 2 and 4 respectively. The results suggest that in terms of capital expenditure, the baseline turbine is more advantageous compared to TIO 1, TIO 2 and TIO 4. The exception to this is TIO 3 which is more advantageous than the baseline turbine.

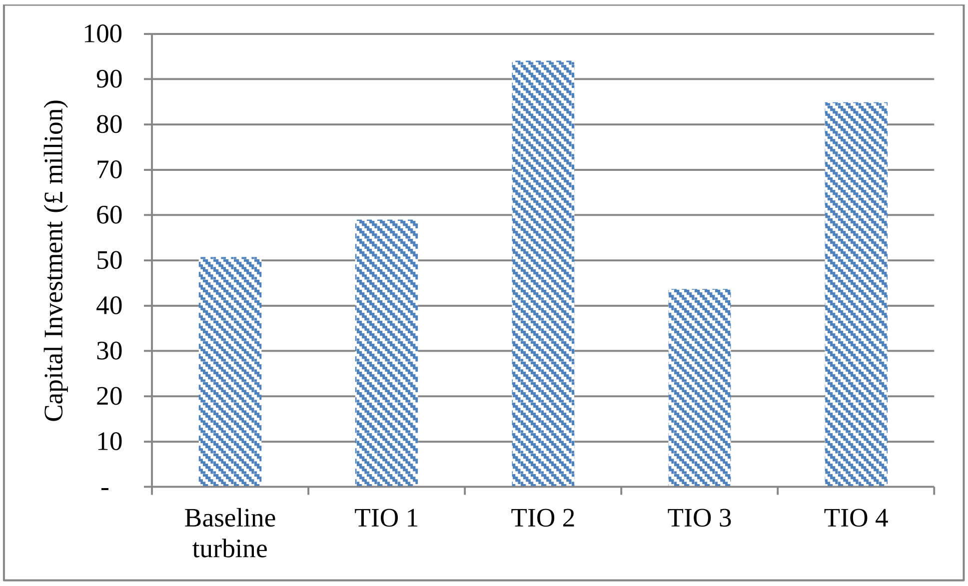


Figure 6-17. Capital investment costs for the wind farm using the different turbine design variations

The capital investment of the wind farm using TIO 1 is £59,033,512, which is 16% higher than for the baseline turbine. The reason for this is higher cost as a result of the advanced design of the blades which permits a 25% increase in blade diameter for TIO 1 compared to the baseline turbine. The cost of the blades for the baseline turbine is £29,375 compared to £133,107 for TIO 1. Hence in terms of capital expenditure, the results suggest that TIO 1 is less advantageous compared to the baseline turbine. Using TIO 2 the capital investment of the wind farm is £94,130,619, which is 85% higher than for the baseline turbine. This is primarily attributed to the cost of carbon fibre used in the tower compared to the cost of steel used in the tower of the baseline turbine. Carbon fibre costs £6.5/kg compared to £0.98/kg for steel. As a result, the cost of the tower for TIO 2 is £629,405 compared to £153,859 for the baseline turbine. TIO 2 is by far the most expensive option and can therefore be said to be the least advantageous design in terms of capital expenditure.

The wind farm has a capital investment of £43,701,834 using TIO 3, which is 14% lower than for the baseline turbine. This is due to the lower cost of the single-stage/permanent magnet generator used in TIO 3 compared to the cost of the direct drive generator used in the baseline turbine as previously highlighted. TIO 3 is the most advantageous option among the turbine design variations in terms of capital expenditure. The capital investment for the wind farm using TIO 4 is £ 84,938,851, which is 67% higher than for the baseline turbine. The cost of carbon fibre used in the tower and 25% increase in blade diameter are the major contributors to the capital investment. The lower cost of the single-stage/permanent magnet generator does however offset the required capital investment. TIO 4 can hence be said to be less advantageous than the baseline turbine in terms of capital expenditure.

6.3.2 Revenue

Figure 6-18 presents the estimated revenue for the wind farm using the baseline turbine and TIOs 1 – 4. For the baseline turbine, TIO 1 and TIO 3, the annual revenue is £17,548,394. The similar results for the aforementioned turbine designs can be attributed to the estimated annual energy output of the wind farm using the said wind turbines. It will be recalled from Section 5.6.1 that the annual energy output of the wind farm using the baseline turbine, TIO 1 and TIO 3 is 212 GWh/year. Using TIO 2 and TIO 4 however, the annual revenue of the wind farm is £17,774,117. This is attributed to the higher estimated annual energy output of 215 GWh/year for the wind farm using both designs. Comparing the turbine designs at different tower heights, TIO 2 and TIO 4 with higher tower heights generated greater revenue. This trend is expected since wind energy increases with height above ground thus, increasing the amount of electricity generated and therefore the associated revenue. The results show that TIO 2 and TIO 4 generate more revenue compared to the baseline turbine, TIO 1 and TIO 3 making TIOs 2 and 4 the most advantageous designs.

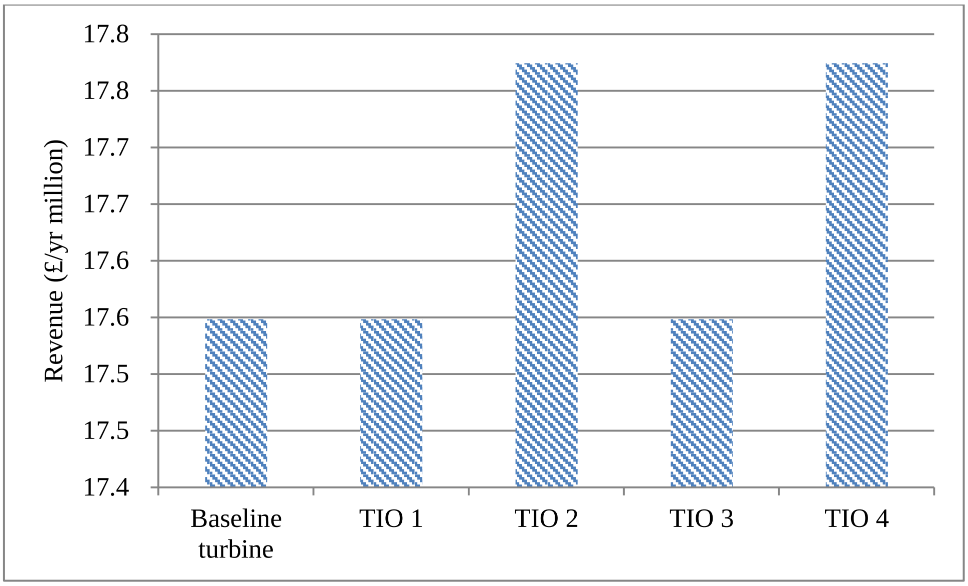


Figure 6-18. Revenue for the wind farm using the different turbine design variations

6.3.3 Operations and Maintenance (O&M)

Figure 6-19 shows the annual O&M costs required for the wind farm using the baseline turbine and TIOs 1 – 4. These costs show the same trends as the annual revenue presented in Section 6.3.2. Annual O&M cost for the baseline turbine, TIO 1 and TIO 3 is £2,200,275. For TIO 2 and TIO 4, the estimated annual O&M cost is £2,218,065. The contributions to the results can again be primarily attributed to the calculated annual energy output of the wind farm using the stated turbine designs. TIO 2 and TIO 4 have higher O&M costs compared to the baseline turbine, TIO 1 and TIO 3. It can therefore be said that the baseline turbine, TIO 1 and TIO 3 are the most attractive options in terms of annual O&M cost.

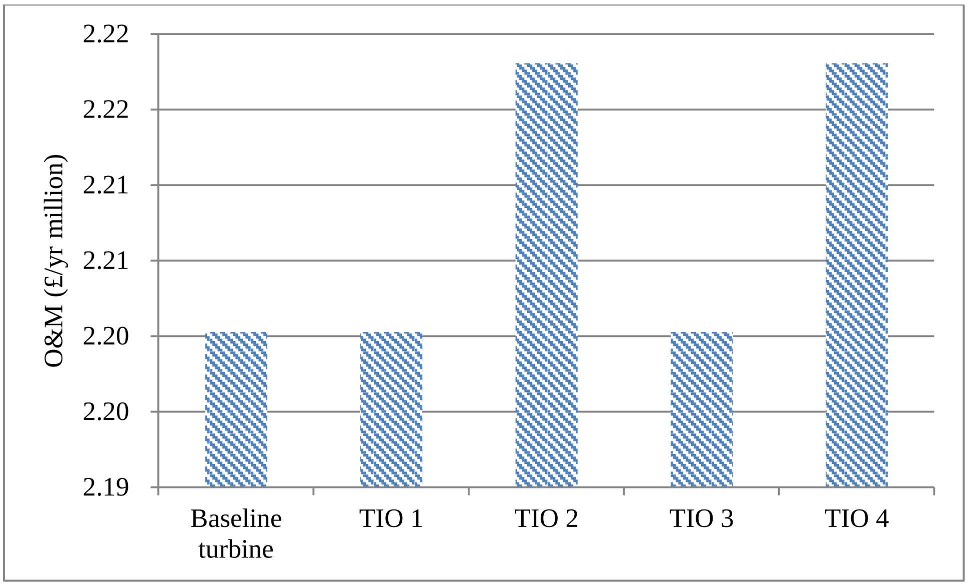


Figure 6-19. O&M costs for the wind farm using the different turbine design variations

6.3.4 Payback Time

Figure 6-20 shows the results of the payback times for the wind farm using the baseline turbine and TIOs 1 – 4. It can be seen that the design variation selected can make a difference in the length of the payback period. Comparing the turbine designs, the payback time for the most advantageous design variation (TIO 3) is 2.8 years versus 6.1 years for the design variation with the longest payback time (TIO 2). According to Gipe (2004), wind turbines with taller hub heights generally have shorter payback times compared to similar models with shorter hub heights. When comparing the turbine designs at different tower heights, TIO 2 and TIO 4 with higher hub heights had longer payback periods. This suggests that the expected annual revenue and capital investment cost (due to carbon fibre use) contribute significantly to the payback period for the two designs.

Since expected revenue and capital investment are the major contributing factors that distinguish the turbine designs, shorter paybacks are most heavily influenced by lower revenue and lower capital investment costs. In this model, the trend in payback times is driven by the capital investment and its influence on how payback time is calculated. Recall from equation 3.13 in Section 3.6.3.1 that payback time is a function of the capital investment, annual revenue, and annual O&M expense. Since revenue and O&M costs are annual energy output dependent in this model, capital investment determines the difference in payback time results. For TIO 2 and TIO 4 with relatively high capital investment, the numerator of equation 3.13 becomes large thus offsetting the effect of higher annual revenue and O&M costs on the payback time. However for the baseline turbine, TIO 1 and TIO 3 with lower capital investment costs, the numerator is reduced and the effect of capital investment becomes less pronounced. Mathematically, this has the effect of reducing the payback time.

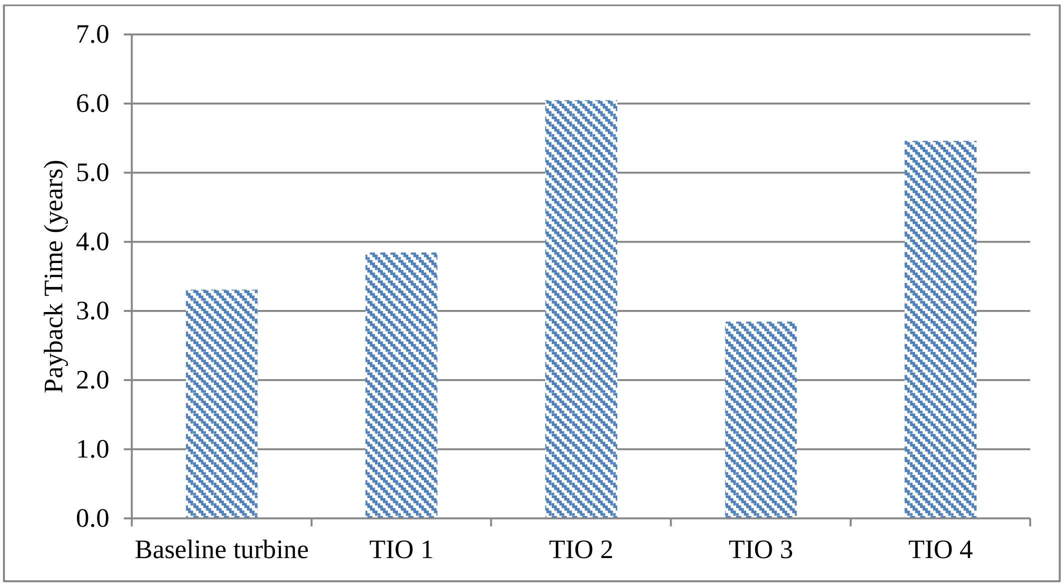


Figure 6-20. Payback times for the wind farm using the different turbine design variations

This observation offers insight into the payback time results for the wind farm. TIO 3 has the lowest capital investment cost of the design variations. This causes the capital investment cost to have the least effect on the annual revenue and O&M cost. As a result, a payback value of 2.8 years is calculated implying that TIO 3 is the most advantageous design option for the wind farm. The baseline turbine has the second lowest capital investment cost. Thus, the capital investment cost has a larger effect on the annual revenue and O&M cost compared to TIO 3. Consequently, a payback time of 3.3 years is calculated implying that the baseline turbine is the second most advantageous design option for the wind farm. TIO 1 has the third lowest capital investment cost of the design variations. Hence, the capital investment cost has a larger effect on the annual revenue and O&M cost compared to TIO 3 and the baseline turbine. A payback value of 3.8 years is calculated as a result suggesting that TIO 1 is the design option with the median economic payback value for the wind farm. TIO 2 and TIO 4 have the highest capital investment costs. Accordingly, the capital investment cost for both designs have the most effect on the annual revenue and O&M cost. As a result, payback values of 6.1 years and 5.5 years were calculated for TIO 2 and TIO 4 respectively suggesting that both designs are the least advantageous for the wind farm.

6.3.5 Discussion

The economic assessment provides insight into use of the different design variations on the wind farm and demonstrates how capital investment for the different design variations results in differing payback time results. Analysis of the different turbine designs revealed that capital investment cost is the most significant factor influencing the economic success of the turbine designs. Capital investment is most significant because even with higher annual revenue and O&M costs for TIO 2 and TIO 4, the trend in payback time results for the baseline turbine and TIOs 1 – 4 were similar to the capital investment results as illustrated in Figure 6-17 and Figure 6-20. Larger capital investment costs increase the time needed to pay back the initial investment. Though it should be noted that the higher capital investment associated with incorporating carbon fibre materials in the tower is not worth the added cost since the design variations with the longest payback periods were shown to be TIO 2 and TIO 4. It is likely that as technology advancements in the production and use of carbon fibre materials increases, wind turbine designs incorporating carbon fibre in their tower structure would have shorter payback periods. This economic assessment also demonstrates the importance of using technological advancements to improve the revenue of the wind farm. Expected annual revenue of the wind farm using TIO 2 and TIO 4 is £17,774,117 compared to £17,548,394 for the baseline turbine. The higher tower heights of TIO 2 and TIO 4 improved access to wind resource hence, the associated revenue. There is also an increase in O&M costs for TIO 2 and TIO 4 since it is calculated primarily as a function of annual energy output. According to Fingersh et al. (2006), different wind turbine designs may have different O&M costs due to varying complexity. The results for TIO 2 and TIO 4 therefore indicate that O&M costs can change considerably between installations of the same turbine based on tower height or other operational factors.

6.3.6 Comparison of results with Literature

Few studies on the economic assessment of wind farms in Western Europe are available in literature for comparison. The estimated payback times for wind farms in different geographical locations (Prats et al., 2011 – 10 MW onshore wind farm in Cuba comprising G52-850 KW turbines; Rehman, 2005 - 30 MW onshore wind farm in Saudi Arabia consisting of 1.5 MW turbines; Renewables First, 2015 – A UK based engineering consultancy specializing in wind power; El-Osta and Kalifa, 2003 – 6 MW wind farm in Libya consisting of 1.5 MW turbines) are listed in Figure 6-21.

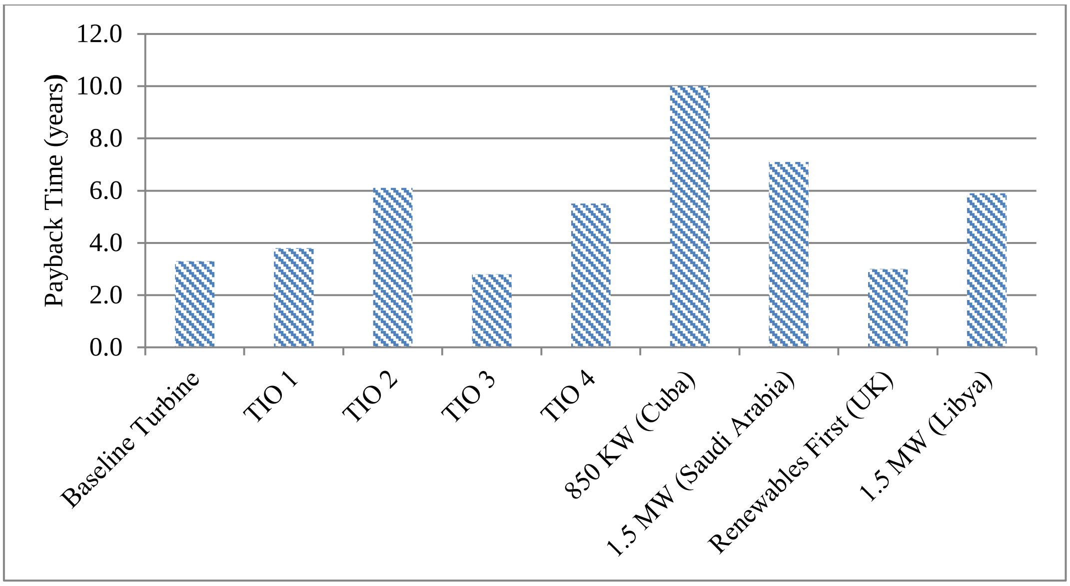


Figure 6-21. Estimated payback times for the wind farm using the different design variations compared with literature

The payback times for the wind farm in this study are estimated at between 2.8 and 6.1 years. As it can be seen from Figure 6-21, estimates of payback times for the wind farms obtained from literature vary among the different studies. The payback times estimated for the wind farm in this study are within the ranges reported by the other sources. The differences are mostly due to the following reasons:

- Location of the wind farm (e.g. costs differ within a country and even more so between countries. In the case of wind farms, the availability of wind resource differs greatly among countries)

- Size of the wind turbines (i.e. smaller turbines have longer payback times compared to larger turbines)
- The economic data and assumptions (e.g. discount rate assumed for the economic analysis, cost data etc.)
- Wind farm operating parameters (i.e. rated capacity, capacity factor, lifetime)

6.3.7 Section Conclusion

In this section the economic sustainability of design variations for a 1.5 MW wind turbine on a wind farm is examined through case studies. In order to evaluate the economics of the wind farm using the design variations, first, capital investment costs for the baseline turbine and TIOs 1 – 4 were estimated. Then for each design variation, revenue and O&M costs were estimated. In determining the most advantageous design variation, payback time of the wind farm using each turbine design is considered. With the results obtained the following conclusions are drawn.

Firstly, with respect to the capital investment, TIO 2 and TIO 4 were the most expensive options. The results suggest that carbon fibre use in the tower of both designs is the primary reason for their higher cost. In other words, the incorporation of carbon fibre materials significantly increases costs associated with capital expenditure.

Secondly, with regards to revenue and O&M costs, similar conclusions can be drawn. The higher revenue and O&M costs for the wind farm using TIO 2 and TIO 4 can be attributed to their higher tower heights. Therefore, it is shown that higher tower height increases the amount of electricity generated, revenue and associated O&M costs.

Thirdly, when comparing the payback time of the wind farm using the different design variations, the results were quite clear. With the incorporation of the technological advancements, TIO 3 is the most advantageous design option for the wind farm.

Therefore, when all the criteria are considered, the potential investor must decide whether the economic benefits for a particular design are worth the investment.

Chapter 7 Conclusions, Recommendations & Future Work

This research has developed an integrated methodology for sustainability assessment of design variations for a wind turbine taking into account environmental, data uncertainty analysis and economic aspects. The methodology has been applied to a 1.5 MW wind turbine for an assessment of the current situation and potential technology improvement opportunities. The latter involved developing a range of potential scenarios in an attempt to find out the most sustainable option for providing grid electricity. The development of the scenarios has been driven and informed by research and scientific developments based on NREL 1.5 MW wind turbine technology forecasting studies, primarily due to the potential for technological advancements to reduce the cost and increase the performance of wind turbines in order to achieve the competitiveness needed for the large investments foreseen. The scenarios depict four different approaches to technological advancements for a 1.5 MW wind turbine: (i) one TIO in which stiffer carbon-fibre materials are used allowing for 25% rotor growth and a 2% reduction in tower mass, (ii) one based on new tower concepts using carbon-fibre materials and power production at 100 meters compared to 65 meters, (iii) one based on the use of permanent magnet generators that use permanent magnets instead of copper wound rotors, and (iv) one which is a combination of all the TIOs. The developed methodology, described in Chapter 3, involves life cycle assessment, data uncertainty propagation in LCA and economic analysis of the baseline situation and scenarios to help identify the most sustainable design option.

Therefore, the objectives of this research as stated in Chapter 1 have been met as follows:

- An integrated methodology has been developed to enable identification of the most sustainable design variation for a wind turbine (Chapter 3);
- A life-cycle model for an existing 1.5 MW wind turbine has been developed (as a baseline scenario) and evaluated using life cycle assessment, a hybrid DQI-statistical method for uncertainty analysis and life cycle costing (Chapters 5 & 6);
- Technological advancements have been identified for a 1.5 MW wind turbine. These include improved blade, tower and generator designs (Chapter 3);

- Technology improvement opportunities (TIOs 1 – 4) for a 1.5 MW wind turbine have been evaluated using life cycle assessment, a hybrid DQI-statistical method for uncertainty analysis and life cycle costing (Chapters 5 & 6);

The main conclusions from this study are summarised in Section 7.1 below. This is followed by policy recommendations in Section 7.2, suggestions for future work in Section 7.3 and finally, concluding remarks in Section 7.4.

7.1 Conclusions

This section summarises the conclusions that can be drawn from this study regarding the environmental, data uncertainty propagation and economic aspects of the scenario analysis (baseline case and potential technology improvement opportunities) for a 1.5 MW wind turbine.

7.1.1 Baseline Case

The baseline case refers to a representative version of a 1.5 MW wind turbine. The major conclusions from the environmental, data uncertainty propagation and economic assessment are as follows (see Chapter 6 for details).

- The uncertainty analysis results show that if Enercon had rejected the E-66 wind turbine design at the conceptual design stage, in terms of embodied carbon, there would have been an about 85% probability Enercon may have lost the chance to reduce carbon emissions with the design. Thus, it is a good design in terms of embodied carbon savings. In terms of embodied energy if the E-66 design was rejected, there would have been a 50% probability Enercon may have lost the chance to reduce the primary energy consumed during manufacture.
- The LCA results for the wind farm show that ODP, MAETP, HTP and TETP are the environmental categories with the highest contribution to impacts and are largely due to the emissions from steel and copper production for the generators, towers and grid connections. The majority of contributions to the other environmental categories are caused by emissions due to the production of iron, steel and fiberglass, with steel having a considerable contribution towards these environmental categories.

- The capital investment for the wind farm is estimated at £50,795,530, with the revenue and O&M costs estimated to be £17,548,394 and £2,200,275 respectively. Payback time for the wind farm is calculated to be 3.3 years.
- Improving electricity generation associated with the supply of grid electricity using 1.5 MW wind turbines would not only increase performance but also will have effects on the natural environment as well as economic aspects. While the use of 1.5 MW wind turbines has reduced gradually over the years with the introduction of larger turbine sizes, there is still scope for significant improvement in this size category.

7.1.2 Technology Improvement Opportunities

Four technology improvement opportunities have been developed for a 1.5 MW wind turbine and the major conclusions from the environmental, data uncertainty propagation and economic assessment results are as follows (see Chapter 6 for details).

7.1.2.1 Uncertainty Analysis

- If the design for TIO 1 is accepted by a manufacturer, in terms of embodied carbon, there will be an about 85% probability that the manufacturer may lose the chance to reduce carbon emissions with this design. Hence, it is not a good design in terms of embodied carbon savings. In terms of embodied energy, if the design is accepted, there will be a 40% probability that the manufacturer may lose the chance to reduce the primary energy consumed. This design thus performs better in terms of embodied energy savings.
- Results show that for embodied carbon, if the design for TIO 2 is accepted, there is almost a 99% probability the manufacturer may lose the chance to reduce carbon emissions hence making it a bad design. For embodied energy, results show that if this design is accepted, there is about a 20% probability the manufacturer may lose the chance to reduce the primary energy consumed making it a good design in terms of embodied energy savings.
- If the design for TIO 3 is accepted, results show that for embodied carbon, there will be a 15% probability that the manufacturer may lose the chance to reduce carbon emissions with this design. It is therefore a good design in terms of embodied carbon savings. For embodied energy, results show that if this design is accepted, there is about a 65% probability the manufacturer may lose the

chance to reduce the primary energy consumed. This design therefore performs better in terms of embodied carbon savings.

- In terms of embodied carbon, if the design for TIO 4 is accepted, there would be about a 99% probability that the manufacturer may lose the chance to reduce carbon emissions making it a bad design. For embodied energy, results show that if this design is accepted, the probability that the manufacturer may lose the chance to reduce the primary energy consumed is about 15% making it a good design in terms of embodied energy savings.

7.1.2.2 Life cycle Environmental Aspects

- Results for the wind farm using TIO 1 show that the contribution to impacts increased for five environmental categories, 6.6% higher ADP, 2.4% higher AP, 0.14% higher EP, 5.9% higher GWP and 1.2% higher POP compared to the baseline turbine. This is largely due to steel and copper production for the generators, towers and grid connections as well as higher material mass of TIO 1.
- Using TIO 2 on the wind farm showed an increase in contributions to three environmental categories, 41.6% higher ADP, 16% higher AP and 40.7% higher GWP, compared to the baseline turbine. This is mainly attributed to the production of glass-reinforced nylon, steel and copper and is largely due to the high energy and emission intensity of glass-reinforced nylon as well as the large tower mass.
- ODP, POP and TETP are the environmental categories with the highest contributions for the wind farm using TIO 3. Overall, lower contributions to all the environmental categories were observed for TIO 3 compared to the baseline turbine. The reason for this is attributed to the reduced generator mass due to iron use in the rotors instead of copper.
- For TIO 4, increased contributions towards ADP – 37% higher, and GWP – 34.8% higher, are observed for the wind farm compared to the baseline turbine. The reason for this mainly is attributed to the production of glass-reinforced nylon as a result of its use in the blade and tower, and lower environmental footprint of iron due to the reduced generator mass.
- The comparison of TIO 2 and TIO 4 to the baseline turbine shows the disadvantage of both designs with respect to ADP and GWP. Higher capacity

factors experienced by the wind farm using both designs did not offset the higher environmental costs as a result of the increased use of glass-reinforced nylon in both designs. TIOs 2 and 4 have lower contributions to the environmental categories EP, ODP, MAETP, FAETP, HTP, POP and TETP compared to the baseline turbine. The exception is AP where TIO 2 has a 13.8% higher contribution and TIO 4 has a 13.4% lower contribution compared to the baseline turbine.

7.1.2.3 Economic Aspects

- The capital investment for the wind farm using TIO 1 is estimated to be £59,033,512, with the revenue and O&M costs estimated at £17,548,394 and £2,200,275 respectively. Payback time for the wind farm using TIO 1 is calculated to be 3.8 years.
- Using TIO 2 the capital investment of the wind farm is estimated to be £94,130,619. Revenue and O&M costs are calculated to be £17,774,117 and £2,218,065 respectively while payback time is estimated to be 6.1 years.
- Capital investment for the wind farm using TIO 3 is estimated to be £43,701,834, with the revenue and O&M costs estimated at £17,548,394 and £2,200,275 respectively. The payback time is estimated to be 2.8 years.
- Results for the wind farm using TIO 4 give capital investment as £84,938,851. Revenue and O&M costs are calculated to be £17,774,117 and £2,218,065 respectively while payback time is estimated to be 5.5 years.

7.1.3 Comparison of Sustainability Indicators for the Different 1.5 MW Wind Turbine Design Options

In real life, decisions are typically made by comparing different options on several, often conflicting, criteria (Dorini et al., 2010). Normally, there is usually no overall best option, as switching between different options is likely to result in an improvement in one criterion and deterioration in some other criteria. The different scenarios presented in this study have different advantages and disadvantages making the choice among them difficult. To aid identification of the most sustainable 1.5 MW wind turbine design variation, the integrated methodology has been used and the following conclusions apply:

- The baseline turbine (with the best embodied carbon and embodied energy performance) is the most sustainable design option in terms of an embodied energy and embodied carbon saving scheme. Its wind farm life cycle impacts and payback time also perform well compared to TIOs 1 - 4 making it an attractive option.
- TIO 3 performs slightly worse than the baseline turbine in terms of embodied energy savings while having similar embodied carbon results with the baseline turbine. It however performs best in terms of wind farm life cycle environmental impacts and payback time compared to the baseline turbine. TIO 3 hence ranks as a very sustainable option.
- Increasing the tower height of TIOs 2 and 4 leads to poor embodied carbon performance but good embodied energy savings results for both designs. The increased capacity factor of the wind farm using both designs leads to reduced life cycle environmental impacts, compared to the baseline turbine, across most of the environmental categories with the exception of ADP and GWP. Despite this fact, the payback times for the wind farm using both designs make them the least preferred option.
- TIO 1 has better embodied carbon and embodied energy savings results compared to TIOs 2 and 4. It however has the worst wind farm life cycle environmental performance with higher contributions to five environmental categories compared to the baseline turbine. The payback time is reasonable compared to TIOs 2 and 4. This design option can be considered if taking into account increased energy capture at reasonable capital investment costs (compared to TIOs 2 and 4).
- Overall, using the integrated methodology, TIO 3 can be said to be the most sustainable 1.5 MW wind turbine design option for future grid electricity supply.

7.2 Policy Recommendations

The trade-offs highlighted by the results of this study illustrate the importance of thoroughly considering a range of sustainability aspects in order to arrive at informed and robust decisions. In the context of 1.5 MW wind turbine design options, a number of policy recommendations can be made based on this study:

7.2.1 General Recommendations

- Assessment of technical, environmental and economic aspects should be at the core of the decision-making process regarding potential 1.5 MW wind turbine design options to ensure that all relevant sustainability indicators have been considered.
- An integrated approach is essential to ensure that there is a balanced comparison between the different sustainability indicators for the wind turbine design options.

7.2.2 Recommendations for Long Term Sustainable Grid Electricity

- An approach purely based on economics will favour TIO 3 resulting in low capital investment costs and payback time. With these advantages, it can be suggested that directives encouraging development and use of single-stage/permanent magnet generators in 1.5 MW wind turbines is desirable. This also includes larger turbine sizes, their role of which is currently being debated in industry. This recommendation is consistent with the decision by the International Energy Agency (IEA, 2013) to reduce the relative costs of wind energy technologies.
- Despite the increased capacity factors that could be attained using TIOs 2 and 4, there is also higher investment risk due to the fact that they are both capital intensive. This risk can be reduced by governments through direct subsidy or market frameworks. In the UK, the “contract-for-difference” system which will eventually replace the Renewable Obligation Order and recently introduced Green Investment Bank demonstrates the government’s willingness to address this.
- There is a likelihood attempts to reduce GWP will worsen other environmental categories such as AP, EP and POP (depending on the design option chosen). These impacts tend to be due to high material requirements (particularly for TIO 1) and can therefore be reduced by end-of-life recycling. The improvement of recycling rates should hence be a priority and government policies introducing measures to provide tax benefits for companies that use recycled materials would be beneficial.
- In countries with large wind power penetration, improved energy supply is an ongoing undertaking (although this clearly depends on government policies in

these countries). The higher capacity factors of TIO 2 and TIO 4 means that increase in annual energy output should allow for the exploitation of more expensive design alternatives. However to mitigate this risk, government policies should be open to technological advancements on which its stance is not clear, such as the use of carbon fibre given its environmental characteristics.

- At the conceptual design stage, the main barrier for the implementation of TIOs 1, 2 and 4 in industry is the fact that use of carbon fibre materials is still in its early developmental stages, requiring significant work for the estimation of its energy and environmental potential as well as financial support for R&D projects. While carbon fibre materials are known for their stiffness, the use of these materials in wind turbine systems has been mostly limited due to the lack of appropriate supporting policies in industry and insufficient financial incentives. Governments should therefore aim to strengthen current policies that encourage R&D using carbon fibre materials within the industry.

7.3 Future Work

The following suggestions are recommended for future work:

- Further analysis of wind farm using alternative LCIA methodologies besides CML 2001 considered in this study. Due to serious disagreement in results between methodologies, this is particularly relevant for human health impacts.
- Extension of economic assessment to allow for rigorous cost estimation (i.e. taking into consideration alternative investment options, the time value of money, variable rate electricity pricing, energy price escalation, and what happens after payback) to complement the approach used in this study.
- Uncertainty analysis using the HDS approach to analyse technological changes in the development of newer wind turbines and other renewable technologies. This would be another excellent application for the HDS methodology.
- Survey of stakeholders to identify preferences for different sustainability indicators and a comparison of these with the results presented in this study.
- Incorporation of multi-criteria decision analysis into the integrated methodology using different methods (e.g. analytic hierarchy process, pair-wise comparison or multi-attribute value theory), to help identify the most sustainable options based on stakeholder preferences.

7.4 Concluding Remarks

Ensuring sustainability of energy supply in the 21st century is a multifaceted challenge. It is demonstrated in this study that the use of an integrated methodology can provide valuable and in-depth insights into the merits and demerits of different 1.5 MW wind turbine design options, based on the current situation and potential technology improvement opportunities. It is hoped that the integrated methodology and results produced by this research can encourage debate and eventually make significant contributions to energy policy decisions at national levels around the world.

Appendices

Appendix A Uncertainty Analysis Related Information

Table A-1. Composition of materials data for the Enercon E-66 turbine

	Material	**Mass (tons)**
1	Aluminium	0.2
2	Fibre glass	7.5
3	Epoxy resin	4.5
4	Polyethene	0.7
5	PVC	2.1
6	Paint	5.4
7	Rubber	0.2
8	Iron	1.5
9	Steel	144.2
10	Galvanized steel	6.7
11	Copper	15.4
12	Steel sheet	19.2
13	steel (no alloy)	37.3
14	Steel (alloy, high grade)	0.6
15	Steel (alloy, low grade)	10.0
16	Cast Steel	3.7
17	Cast iron	21.0
18	Unsaturated polyester resin	2.2
19	Electronics (plastic)	2.5
20	Steel (for construction)	27.0
21	Gear oil	0.9
22	Light weight concrete	12.0
23	Normal concrete	575.0
	Sum	900.1

Table A-2. Composition of materials data for TIO 1

	Material	**Mass (tons)**
1	Aluminium	0.3
2	CFRP	8.6
3	Epoxy resin	5.9
4	Polyethene	0.9
5	PVC	2.5
6	Paint	5.5
7	Rubber	0.2
8	Iron	1.7
9	Steel	141.3
10	Galvanized steel	6.6
11	Copper	15.4
12	Steel sheet	19.2
13	steel (no alloy)	37.3
14	Steel (alloy, high grade)	0.6
15	Steel (alloy, low grade)	10.0
16	Cast Steel	3.7
17	Cast iron	21.0
18	Unsaturated polyester resin	2.2
19	Electronics (plastic)	2.5
20	Steel (for construction)	27.0
21	Gear oil	0.9
22	Light weight concrete	12.0
23	Normal concrete	575.0
24	Fibre glass	0.9
	Sum	901.4

Table A-3. Composition of materials data for TIO 2

	Material	**Mass (tons)**
1	Aluminium	0.2
2	Fibre glass	7.5
3	Epoxy resin	4.5
4	Polyethene	0.7
5	PVC	2.1
6	Paint	3.8
7	Rubber	0.2
8	Iron	1.5
9	CFRP	88.5
10	Galvanized steel	4.9
11	Copper	15.4
12	Steel sheet	19.2
13	steel (no alloy)	37.3
14	Steel (alloy, high grade)	0.6
15	Steel (alloy, low grade)	10.0
16	Cast Steel	3.7
17	Cast iron	21.0
18	Unsaturated polyester resin	2.2
19	Electronics (plastic)	2.5
20	Steel (for construction)	27.0
21	Gear oil	0.9
22	Light weight concrete	12.0
23	Normal concrete	575.0
	Sum	840.9

Table A-4. Composition of materials data for TIO 3

	Material	**Mass (tons)**
1	Aluminium	0.2
2	Fibre glass	7.5
3	Epoxy resin	4.5
4	Polyethene	0.7
5	PVC	2.1
6	Paint	5.3
7	Rubber	0.2
8	Iron	3.5
9	Steel	144.2
10	Galvanized steel	6.7
11	Copper	6.4
12	Steel sheet	5.2
13	steel (no alloy)	26.9
14	Steel (alloy, high grade)	0.6
15	Steel (alloy, low grade)	10.0
16	Cast Steel	3.7
17	Cast iron	21.0
18	Unsaturated polyester resin	2.2
19	Electronics (plastic)	2.5
20	Steel (for construction)	27.0
21	Gear oil	0.9
22	Light weight concrete	12.0
23	Normal concrete	575.0
	Sum	868.5

Table A-5. Composition of materials data for TIO 4

	Material	**Mass (tons)**
1	Aluminium	0.3
2	Fibre glass	0.9
3	Epoxy resin	5.9
4	Polyethene	0.9
5	PVC	2.5
6	Paint	3.8
7	Rubber	0.2
8	Iron	3.7
9	CFRP	97.0
10	Galvanized steel	4.8
11	Copper	6.4
12	Steel sheet	5.2
13	steel (no alloy)	26.9
14	Steel (alloy, high grade)	0.6
15	Steel (alloy, low grade)	10.0
16	Cast Steel	3.7
17	Cast iron	21.0
18	Unsaturated polyester resin	2.2
19	Electronics (plastic)	2.5
20	Steel (for construction)	27.0
21	Gear oil	0.9
22	Light weight concrete	12.0
23	Normal concrete	575.0
	Sum	813.7

Table A-6. Results from the deterministic estimation of embodied carbon and embodied energy for the different wind turbine design options

Wind turbine design option	**Deterministic result for embodied carbon (ton CO_2)**	**Deterministic result for embodied energy (GJ)**
Baseline Turbine	932	11910
TIO 1	1070	13738
TIO 2	2472	31846
TIO 3	849	10721
TIO 4	2533	32533

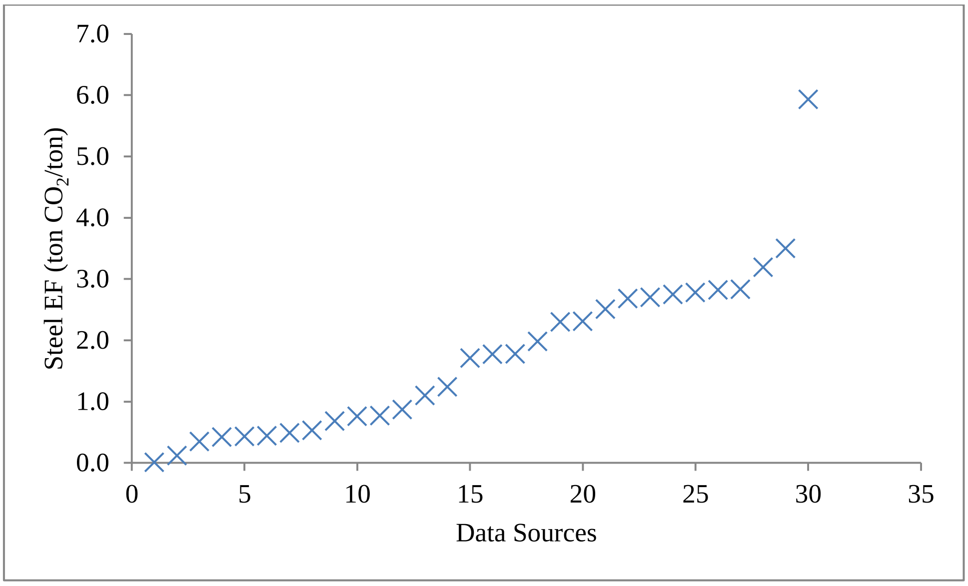


Figure A-1. Raw data points for Steel EF

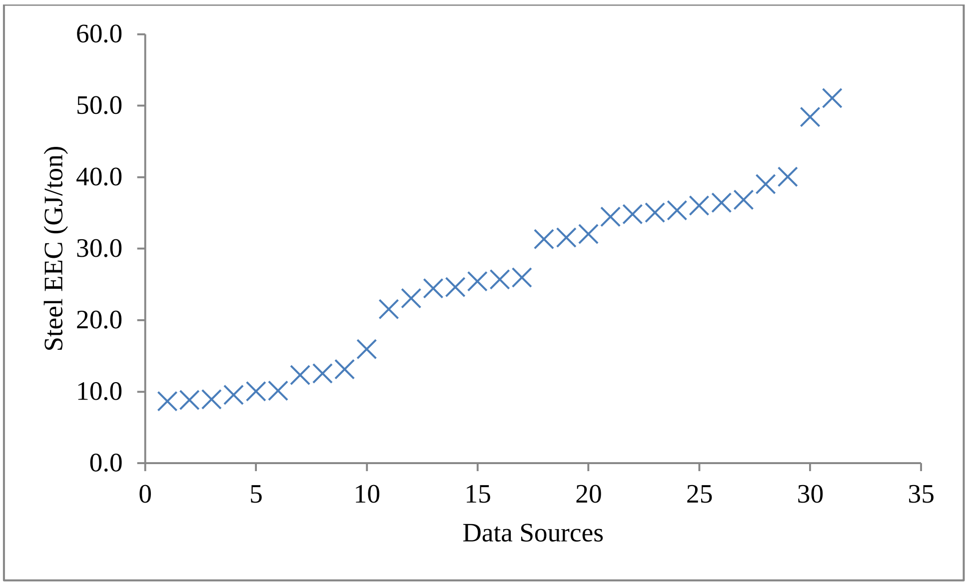


Figure A-2. Raw data points for Steel EEC

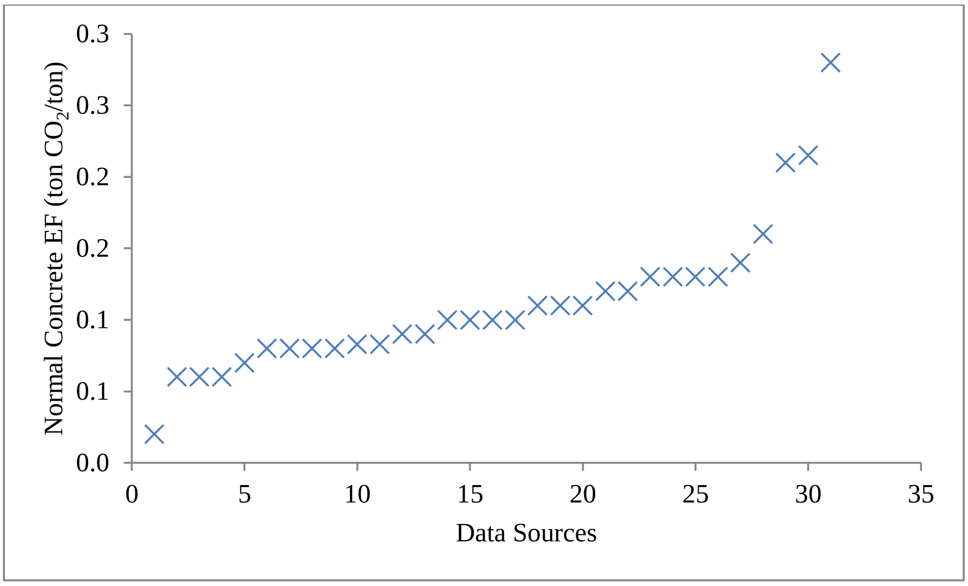


Figure A-3. Raw data points for Normal Concrete EF

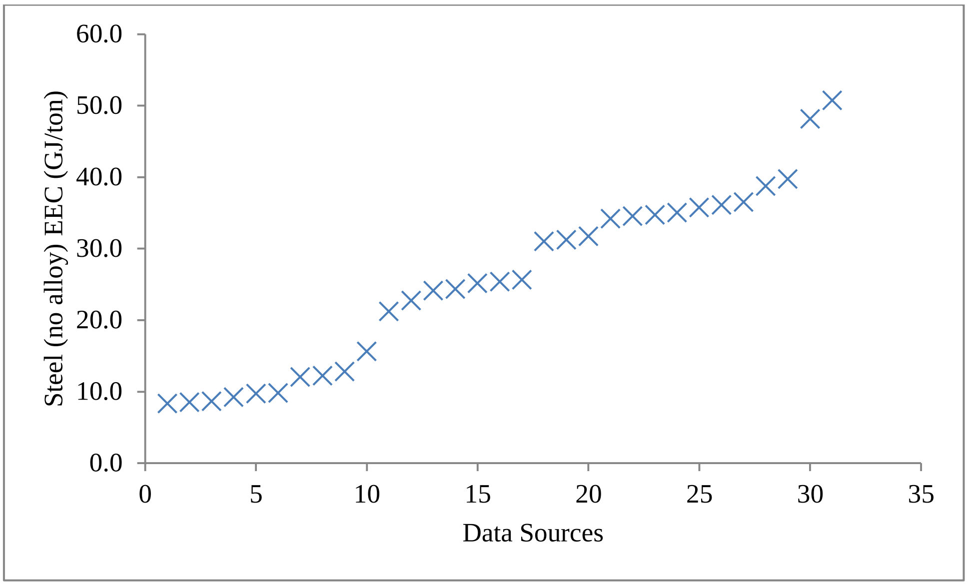


Figure A-4. Raw data points for Steel (no alloy) EEC

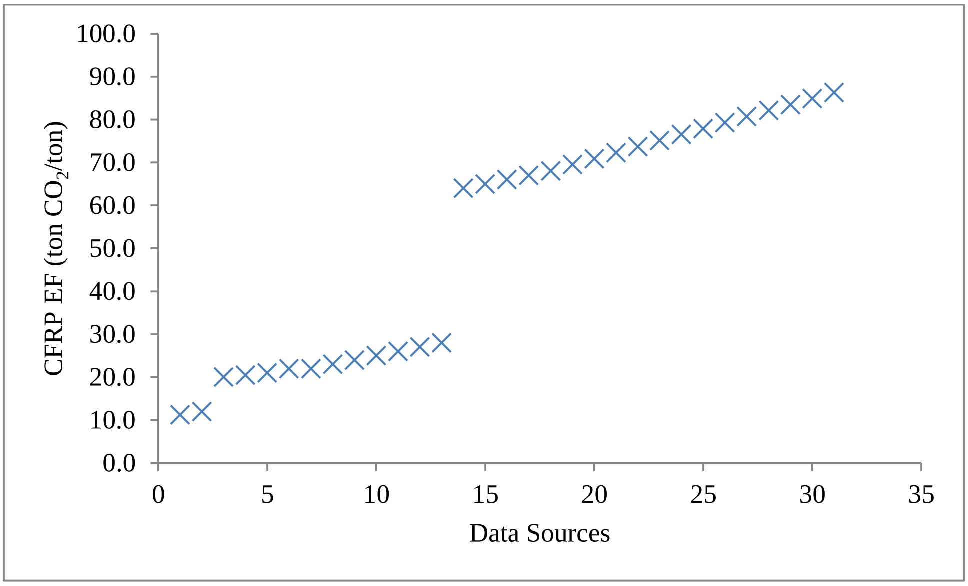


Figure A-5. Raw data points for CFRP EF

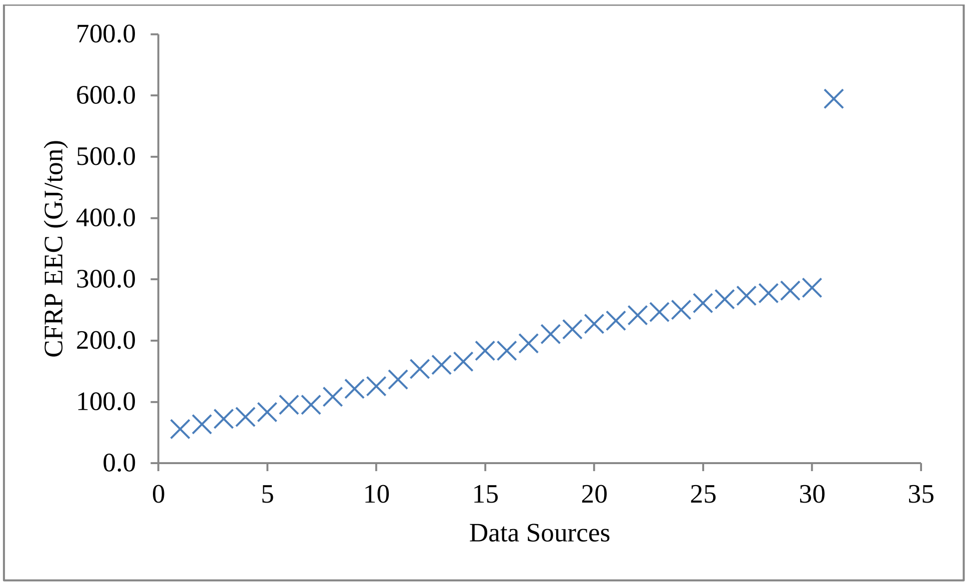


Figure A-6. Raw data points for CFRP EEC

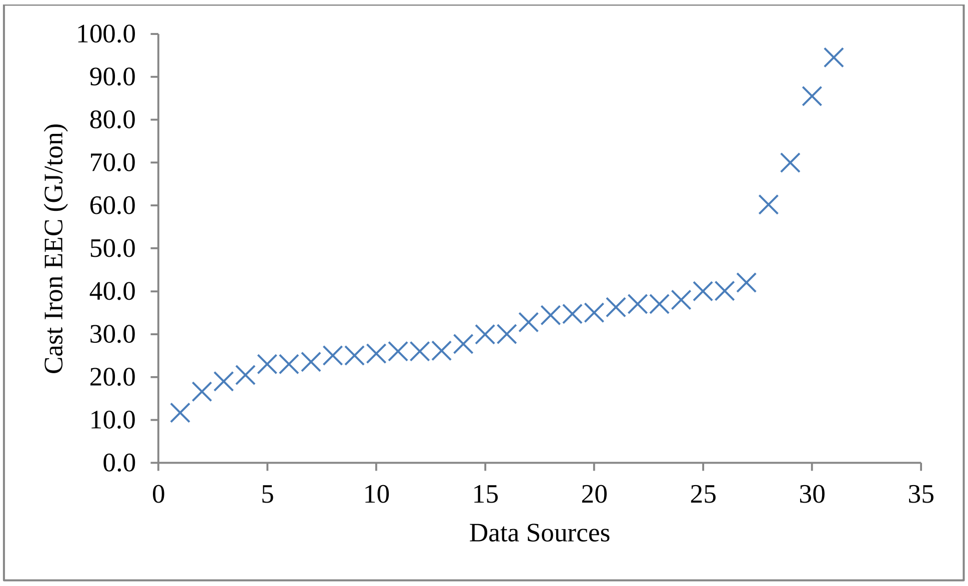


Figure A-7. Raw data points for Cast Iron EEC

Appendix B Wind Farm Lifecycle Related Information

The midpoint impact categories considered in this study are described as follows in Martínez et al. (2009):

Abiotic Depletion Potential: This impact category is concerned with the protection of ecosystem health, human health and human welfare and is associated with the extraction of fossil fuels and minerals due to inputs in the system. The abiotic depletion factor is determined for each extraction of fossil fuels and minerals (kg antimony equivalents/kg extraction) based on rate of de-accumulation and concentration of reserves.

Acidification: This category is associated with acidifying substances that cause a range of impacts on ecosystems, materials, organisms, surface water, groundwater and soil. The major acidifying substances are NH_3, SO_2, HCI and NOx. For emissions to air, acidification potential is defined as the number of H^+ ions produced per kg substance relative to SO_2.

Eutrophication: This category is associated to all impacts due to excessive levels of macro-nutrients in the environment produced by emissions of nutrients to soil, air and water. Phosphorus (P) and Nitrogen (N) are the two nutrients most associated with eutrophication. Eutrophication potentials are often expressed as PO_4 equivalents.

Fresh-water aquatic eco-toxicity: This impact category is associated with the impact on freshwater ecosystems due to the emissions of toxic substances to soil, water and air for an infinite time horizon. For each toxic substance, eco-toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission.

Global Warming Potential: Global Warming Potential can result in adverse effects on material welfare, human health and ecosystem health and is associated with the emissions of greenhouse gases to air. The climate change factor is expressed as global warming potential for 100 years' time horizon, in kg carbon dioxide/kg emission.

Human toxicity: This impact category is associated with exposure and effects of toxic substances for an infinite time horizon. For each toxic substance, human toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission.

Marine eco-toxicity: This impact category is associated with the impact on marine ecosystems. Marine eco-toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission.

Ozone Depletion Potential: This category is associated with the fraction of UV-B radiation reaching the surface of the earth. The World Meteorological Organisation developed the characterisation model and defines the ozone depletion potential of different gasses (kg CFC-11 equivalent/kg emission).

Photochemical oxidation: This category is associated with the formation of reactive substances (largely ozone) that are injurious to ecosystems and human health and might also damage crops. The impact potentials are expressed as an equivalent emission of the reference substance ethylene, C_2H_4.

Terrestrial eco-toxicity: This impact category is associated with the impact on terrestrial ecosystems. Terrestrial eco-toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission.

Wind Data Analysis

The wind speeds from the NOABL database for the Pen y Cymoedd wind farm and meteorological stations at 10 metre heights are shown below:

For 1 km grid square,

Table B-1. Wind speeds for Pen y Cymoedd farm at 10 metres (in m/s)

7.2	7.5	7.9
5.8	6.8	8
3.3	6.2	8.5

Table B-2. Wind speeds for St Athan meteorological station at 10 metres (in m/s)

5.4	5.4	5.3
5.7	5.6	5.4
5.8	5.5	5.2

Table B-3. Wind speeds for Mumbles Head meteorological station at 10 metres (in m/s)

6.2	5.2	5.2
5.9	6.2	5.6
5.9	5.8	6.2

Table B-4. Wind speeds for Sennybridge No 2 meteorological station at 10 metres (in m/s)

6.7	6.5	6.1
6.9	6.4	5.7
6.1	6.3	6

Table B-5. The wind speeds (in m/s) from the MIDAS database for the meteorological stations at 10 metre heights for the period 2005 to 2014 are shown below:

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
St Athan	9.47	9.1	9.75	9.33	10.16	9.2	8.13	9.66	9.43	9.53
Mumbles Head	15.2	12.5	13.7	12.5	14.2	13.5	11.33	13.7	12.7	13.2
Sennybridge No2	7.4	6.87	7.14	6.25	6.74	6.98	5.64	7.38	6.41	6.88

Table B-6. Bill of materials for the Enercon E-66 turbine

	Material	**Mass**	**Unit**	**Total**
	Aluminium	99	kg	
	Fibre Glass	6564	kg	
	Epoxy resin	4548	kg	
	Hardener	1575	kg	
3 Blades	Polyamide	228	kg	
	Polyethene	684	kg	16152
	PVC foam	837	kg	
	PVC	393	kg	
	Paint	552	kg	
	Rubber	165	kg	
	Others (iron)	507	kg	
	Steel	144182	kg	
Tower	Galvanised steel	4695	kg	153094
	Paint	4217	kg	
	Copper	8988	kg	
	Steel sheet	17927	kg	
	Steel (no alloy)	13258	kg	
Generator	Steel (galvanised, low grade)	105	kg	40690
	Steel (alloy, high grade)	14	kg	
	Paint	150	kg	
	Others	248	kg	
	Steel (no alloy)	10780	kg	
	Steel (alloy, low grade)	9101	kg	
	Steel (galvanised, low grade)	1224	kg	

Rest of nacelle	Cast steel	3708	kg	51591
	Cast iron	21027	kg	
	Aluminium	127	kg	
	Copper	293	kg	
	Fibre glass	924	kg	
	Unsaturated polyester resin	2159	kg	
	Electronics	120	kg	
	Paint	504	kg	
	Others	1624	kg	
Grid Connection	Steel sheet	1300	kg	27734
	Steel (alloy, low grade)	927	kg	
	Steel (alloy, high grade)	630	kg	
	Steel (galvanised)	715	kg	
	Steel (for construction)	741	kg	
	Iron	1042	kg	
	Copper	6119	kg	
	PVC	747	kg	
	Gear oil	940	kg	
	Rest of electrics	1065	kg	
	Electronics	1283	kg	
	Light weight concrete	12000	kg	
	Others	225	kg	
Deep foundations	Normal concrete	575000	kg	614709
	Steel (construction)	26300	kg	
	Steel (no alloy)	13243	kg	
	PVC	166	kg	

Table B-7. Bill of materials for TIO 1

	Material	**Mass**	**Unit**	**Total**
3 Blades	Aluminium	129	kg	21049
	CFRP	8554	kg	
	Epoxy resin	5927	kg	
	Hardener	2052	kg	
	Polyamide	297	kg	
	Polyethene	891	kg	
	PVC foam	1091	kg	
	PVC	512	kg	
	Paint	719	kg	
	Rubber	215	kg	
	Others (iron)	661	kg	
Tower	Steel	141298	kg	150032
	Galvanised steel	4601	kg	
	Paint	4133	kg	
	Copper	8988	kg	
	Steel sheet	17927	kg	

Generator	Steel (no alloy)	13258	kg	40690
	Steel (galvanised, low grade)	105	kg	
	Steel (alloy, high grade)	14	kg	
	Paint	150	kg	
	Others	248	kg	
Rest of nacelle	Steel (no alloy)	10780	kg	51591
	Steel (alloy, low grade)	9101	kg	
	Steel (galvanised, low grade)	1224	kg	
	Cast steel	3708	kg	
	Cast iron	21027	kg	
	Aluminium	127	kg	
	Copper	293	kg	
	Fibre glass	924	kg	
	Unsaturated polyester resin	2159	kg	
	Electronics	120	kg	
	Paint	504	kg	
	Others	1624	kg	
Grid Connection	Steel sheet	1300	kg	27734
	Steel (alloy, low grade)	927	kg	
	Steel (alloy, high grade)	630	kg	
	Steel (galvanised)	715	kg	
	Steel (for construction)	741	kg	
	Iron	1042	kg	
	Copper	6119	kg	
	PVC	747	kg	
	Gear oil	940	kg	
	Rest of electrics	1065	kg	
	Electronics	1283	kg	
	Light weight concrete	12000	kg	
	Others	225	kg	
Deep foundations	Normal concrete	575000	kg	614709
	Steel (construction)	26300	kg	
	Steel (no alloy)	13243	kg	
	PVC	166	kg	

Table B-8. Bill of materials for TIO 2

	Material	Mass	Unit	Total
	Aluminium	99	kg	
	Fibre glass	6564	kg	
	Epoxy resin	4548	kg	
	Hardener	1575	kg	
3 Blades	Polyamide	228	kg	
	Polyethene	684	kg	16152
	PVC foam	837	kg	
	PVC	393	kg	
	Paint	552	kg	
	Rubber	165	kg	
	Others (iron)	507	kg	
	CFRP	88472	kg	
Tower	Galvanised steel	2881	kg	93941
	Paint	2588	kg	
	Copper	8988	kg	
	Steel sheet	17927	kg	
	Steel (no alloy)	13258	kg	
Generator	Steel (galvanised, low grade)	105	kg	40690
	Steel (alloy, high grade)	14	kg	
	Paint	150	kg	
	Others	248	kg	
	Steel (no alloy)	10780	kg	
	Steel (alloy, low grade)	9101	kg	
	Steel (galvanised, low grade)	1224	kg	
	Cast steel	3708	kg	
	Cast iron	21027	kg	
Rest of nacelle	Aluminium	127	kg	51591
	Copper	293	kg	
	Fibre glass	924	kg	
	Unsaturated polyester resin	2159	kg	
	Electronics	120	kg	
	Paint	504	kg	
	Others	1624	kg	
	Steel sheet	1300	kg	
	Steel (alloy, low grade)	927	kg	
	Steel (alloy, high grade)	630	kg	
	Steel (galvanised)	715	kg	
	Steel (for construction)	741	kg	
	Iron	1042	kg	
Grid Connection	Copper	6119	kg	27734
	PVC	747	kg	
	Gear oil	940	kg	
	Rest of electrics	1065	kg	
	Electronics	1283	kg	

	Light weight concrete	12000	kg	
	Others	225	kg	
Deep foundations	Normal concrete	575000	kg	614709
	Steel (construction)	26300	kg	
	Steel (no alloy)	13243	kg	
	PVC	166	kg	

Table B-9. Bill of materials for TIO 3

	Material	**Mass**	**Unit**	**Total**
3 Blades	Aluminium	99	kg	16152
	Fibre glass	6564	kg	
	Epoxy resin	4548	kg	
	Hardener	1575	kg	
	Polyamide	228	kg	
	Polyethene	684	kg	
	PVC foam	837	kg	
	PVC	393	kg	
	Paint	552	kg	
	Rubber	165	kg	
	Others (iron)	507	kg	
Tower	Steel	144182	kg	153094
	Galvanised steel	4695	kg	
	Paint	4217	kg	
Generator	Iron	1973	kg	8931
	Steel sheet	3935	kg	
	Steel (no alloy)	2910	kg	
	Steel (galvanised, low grade)	23	kg	
	Steel (alloy, high grade)	3	kg	
	Paint	33	kg	
	Others	54	kg	
Rest of nacelle	Steel (no alloy)	10780	kg	51591
	Steel (alloy, low grade)	9101	kg	
	Steel (galvanised, low grade)	1224	kg	
	Cast steel	3708	kg	
	Cast iron	21027	kg	
	Aluminium	127	kg	
	Copper	293	kg	
	Fibre glass	924	kg	
	Unsaturated polyester resin	2159	kg	
	Electronics	120	kg	
	Paint	504	kg	
	Others	1624	kg	
	Steel sheet	1300	kg	
	Steel (alloy, low grade)	927	kg	
	Steel (alloy, high grade)	630	kg	

Grid Connection	Steel (galvanised)	715	kg	27734
	Steel (for construction)	741	kg	
	Iron	1042	kg	
	Copper	6119	kg	
	PVC	747	kg	
	Gear oil	940	kg	
	Rest of electrics	1065	kg	
	Electronics	1283	kg	
	Light weight concrete	12000	kg	
	Others	225	kg	
Deep foundations	Normal concrete	575000	kg	614709
	Steel (construction)	26300	kg	
	Steel (no alloy)	13243	kg	
	PVC	166	kg	

Table B-10. Bill of materials for TIO 4

	Material	**Mass**	**Unit**	**Total**
3 Blades	Aluminium	129	kg	21049
	CFRP	8554	kg	
	Epoxy resin	5927	kg	
	Hardener	2053	kg	
	Polyamide	297	kg	
	Polyethene	891	kg	
	PVC foam	1091	kg	
	PVC	512	kg	
	Paint	719	kg	
	Rubber	215	kg	
	Others (iron)	661	kg	
Tower	CFRP	88472	kg	93941
	Galvanised steel	2881	kg	
	Paint	2588	kg	
Generator	Iron	1973	kg	8931
	Steel sheet	3935	kg	
	Steel (no alloy)	2910	kg	
	Steel (galvanised, low grade)	23	kg	
	Steel (alloy, high grade)	3	kg	
	Paint	33	kg	
	Others	54	kg	
Rest of nacelle	Steel (no alloy)	10780	kg	51591
	Steel (alloy, low grade)	9101	kg	
	Steel (galvanised, low grade)	1224	kg	
	Cast steel	3708	kg	
	Cast iron	21027	kg	
	Aluminium	127	kg	
	Copper	293	kg	

	Fibre glass	924	kg	
	Unsaturated polyester resin	2159	kg	
	Electronics	120	kg	
	Paint	504	kg	
	Others	1624	kg	
	Steel sheet	1300	kg	
	Steel (alloy, low grade)	927	kg	
	Steel (alloy, high grade)	630	kg	
	Steel (galvanised)	715	kg	
	Steel (for construction)	741	kg	
	Iron	1042	kg	
Grid Connection	Copper	6119	kg	27734
	PVC	747	kg	
	Gear oil	940	kg	
	Rest of electrics	1065	kg	
	Electronics	1283	kg	
	Light weight concrete	12000	kg	
	Others	225	kg	
	Normal concrete	575000	kg	
Deep foundations	Steel (construction)	26300	kg	614709
	Steel (no alloy)	13243	kg	
	PVC	166	kg	

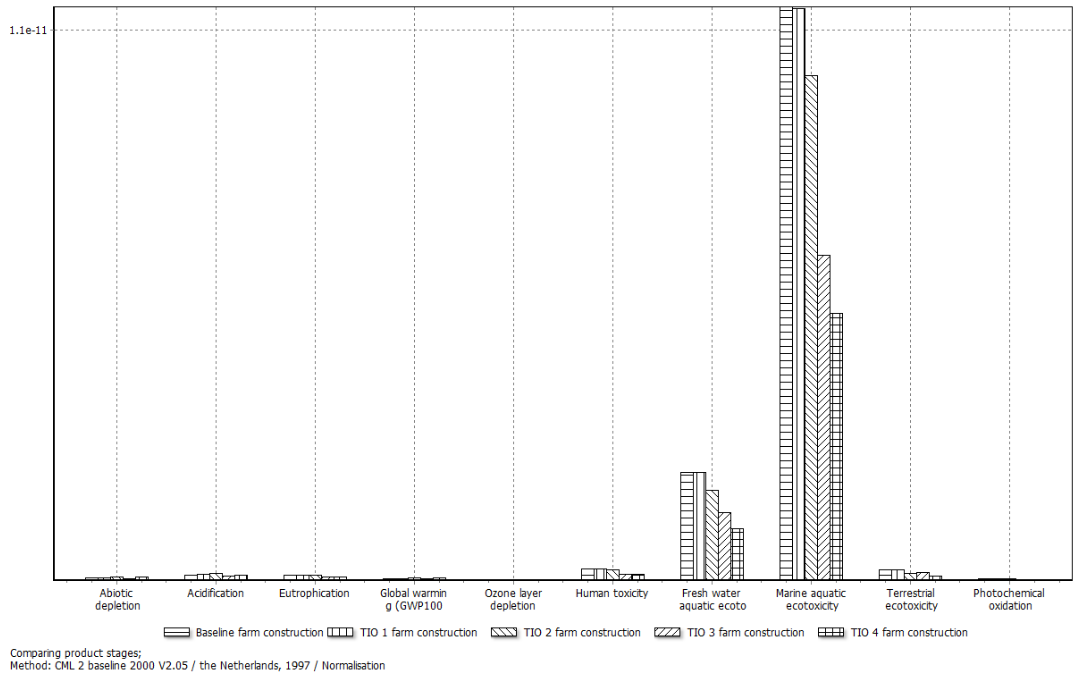


Figure B-1. Normalization results for the comparison between the construction stages of the baseline turbine and TIOs 1 - 4

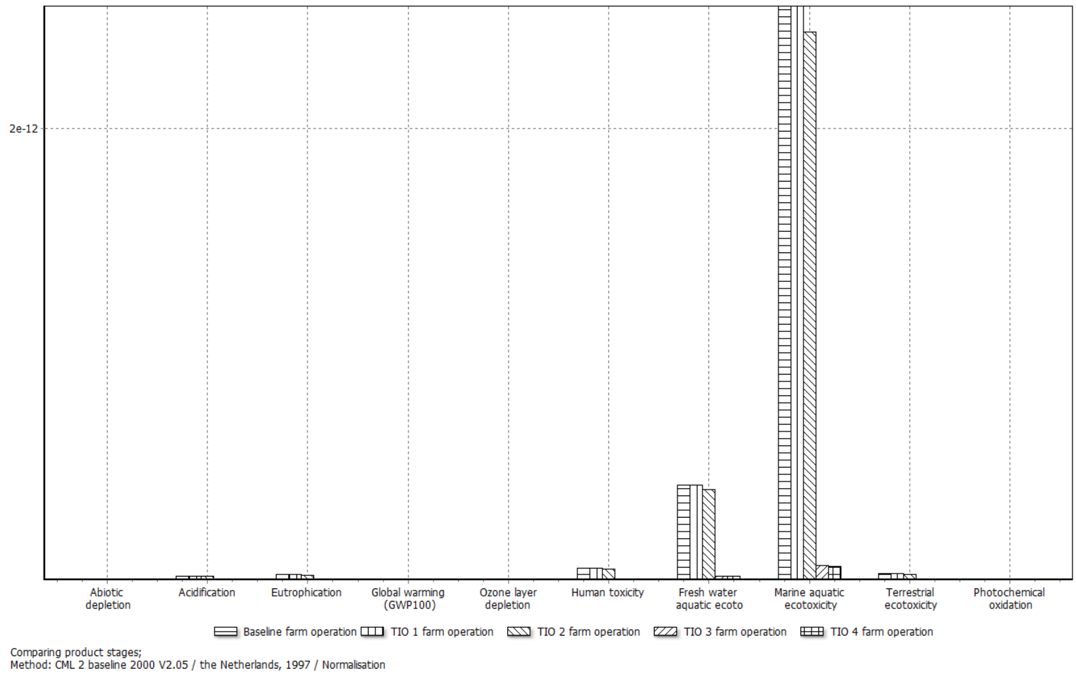


Figure B-2. Normalization results for the comparison between the operation stages of the baseline turbine and TIOs 1 - 4

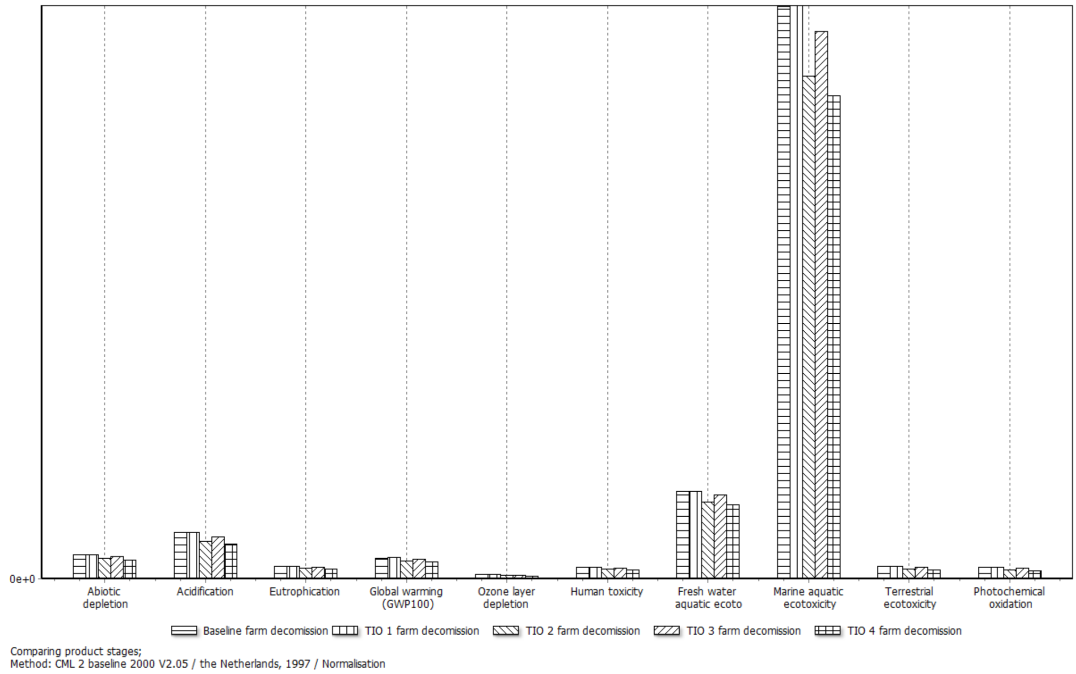


Figure B-3. Normalization results for the comparison between the decommissioning stages of the baseline turbine and TIOs 1 - 4

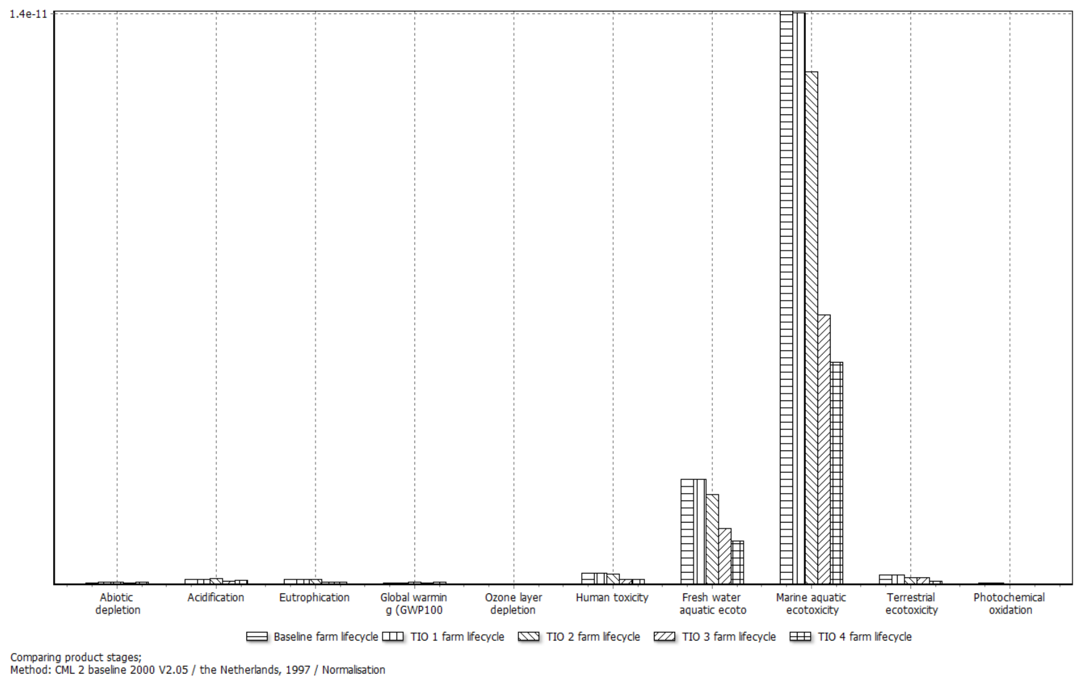


Figure B-4. Normalization results for life cycle environmental impacts of the wind farm for the baseline turbine compared to TIOs 1 – 4

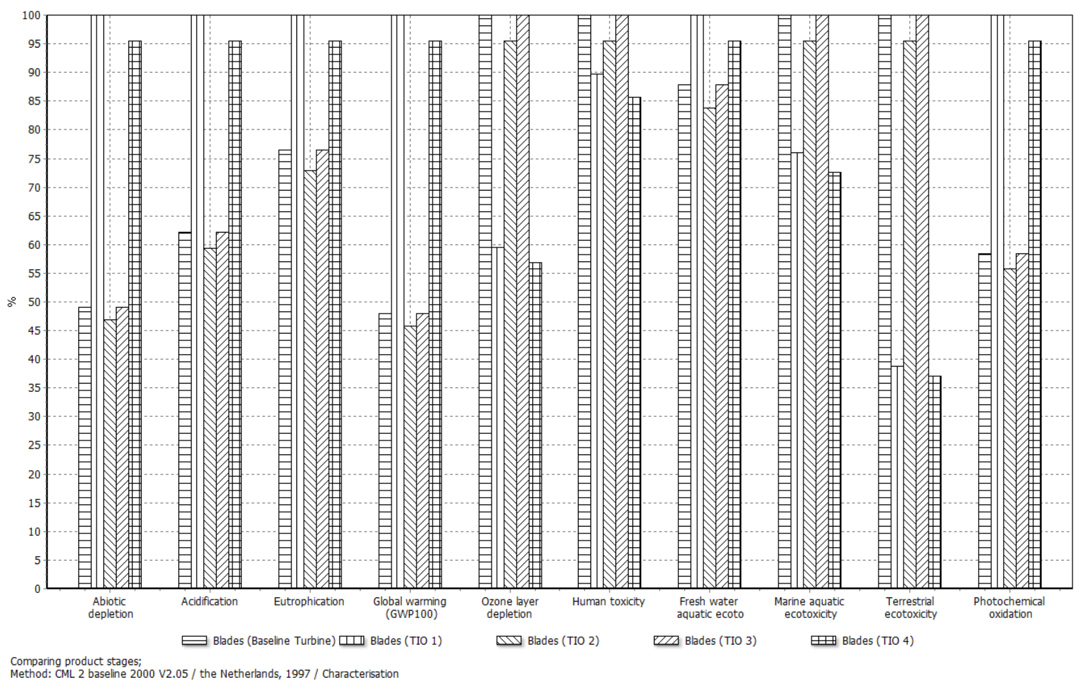


Figure B-5. Characterization results for the comparison between the blades of the baseline turbine and TIOs 1 - 4

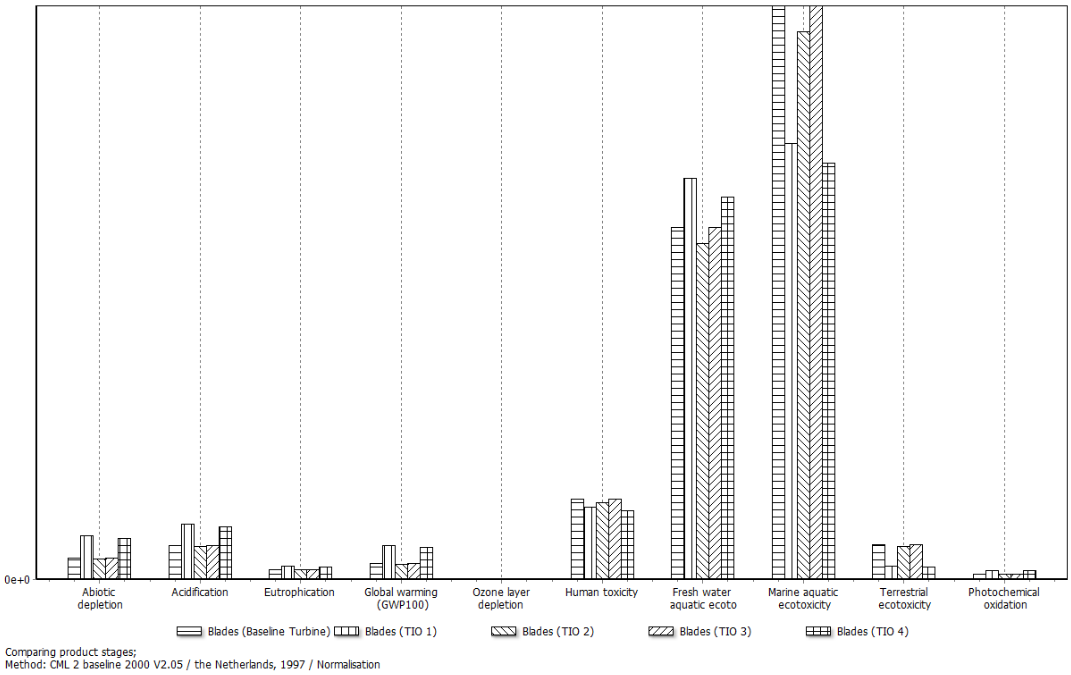


Figure B-6. Normalization results for the comparison between the blades of the baseline turbine and TIOs 1 - 4

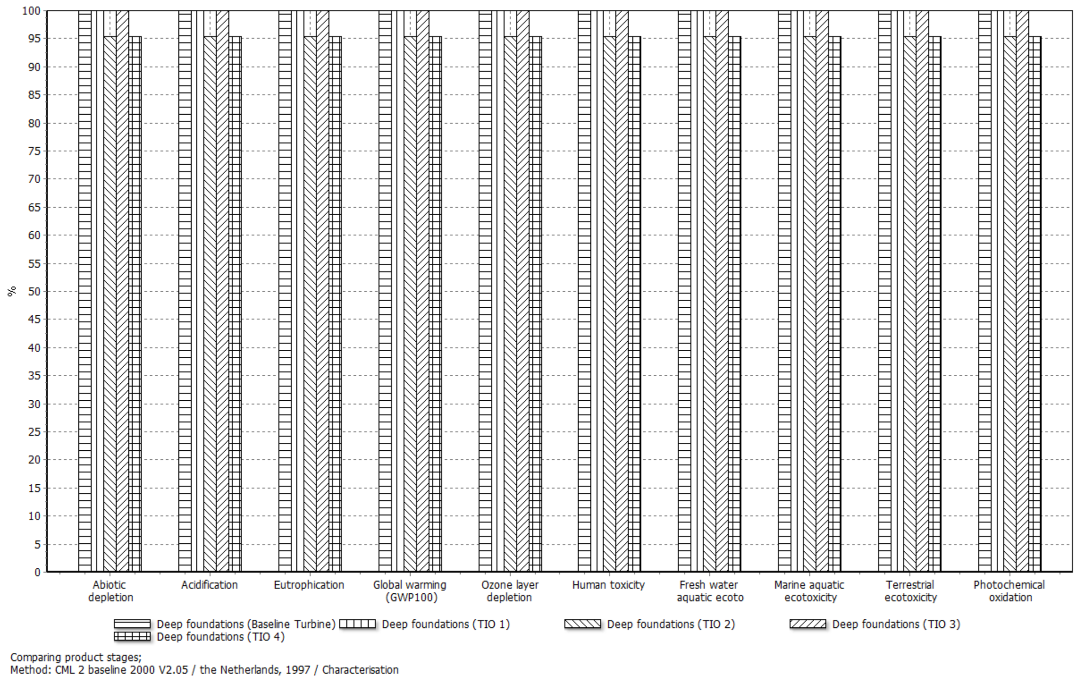


Figure B-7. Characterization results for the comparison between the foundations of the baseline turbine and TIOs 1 - 4

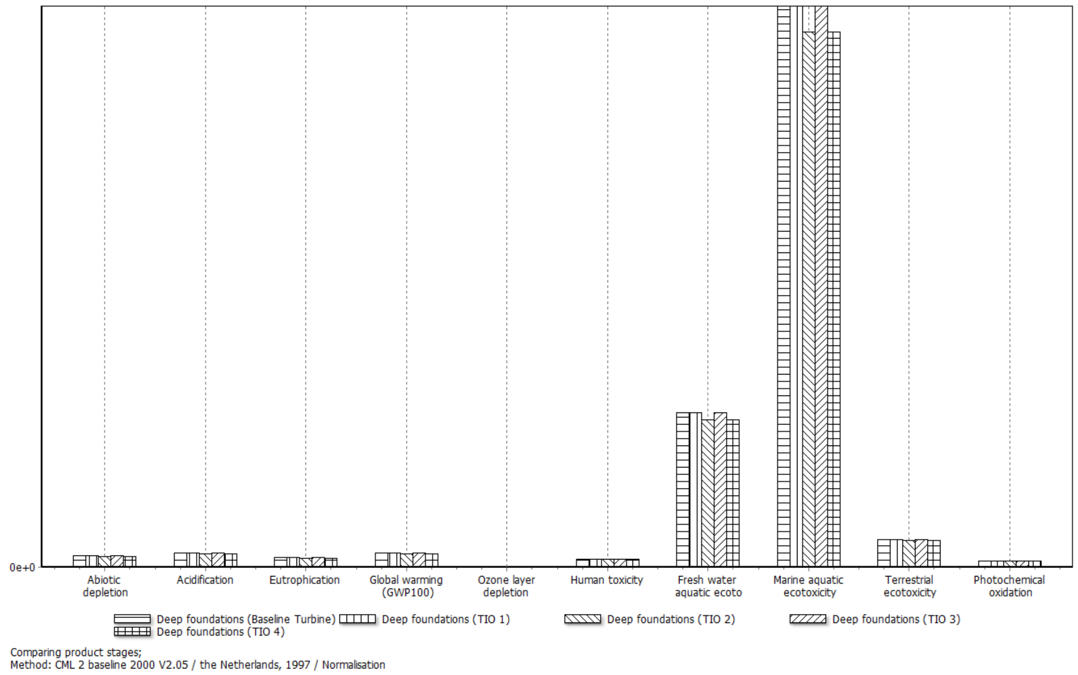


Figure B-8. Normalization results for the comparison between the foundations of the baseline turbine and TIOs 1 - 4

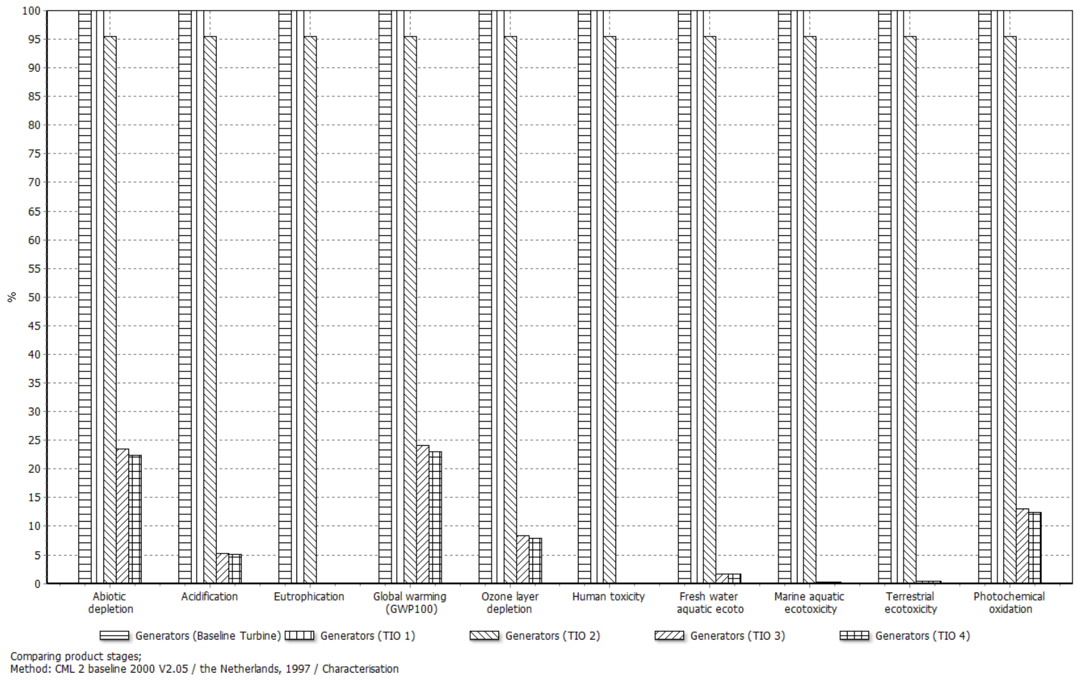


Figure B-9. Characterization results for the comparison between the generators of the baseline turbine and TIOs 1 - 4

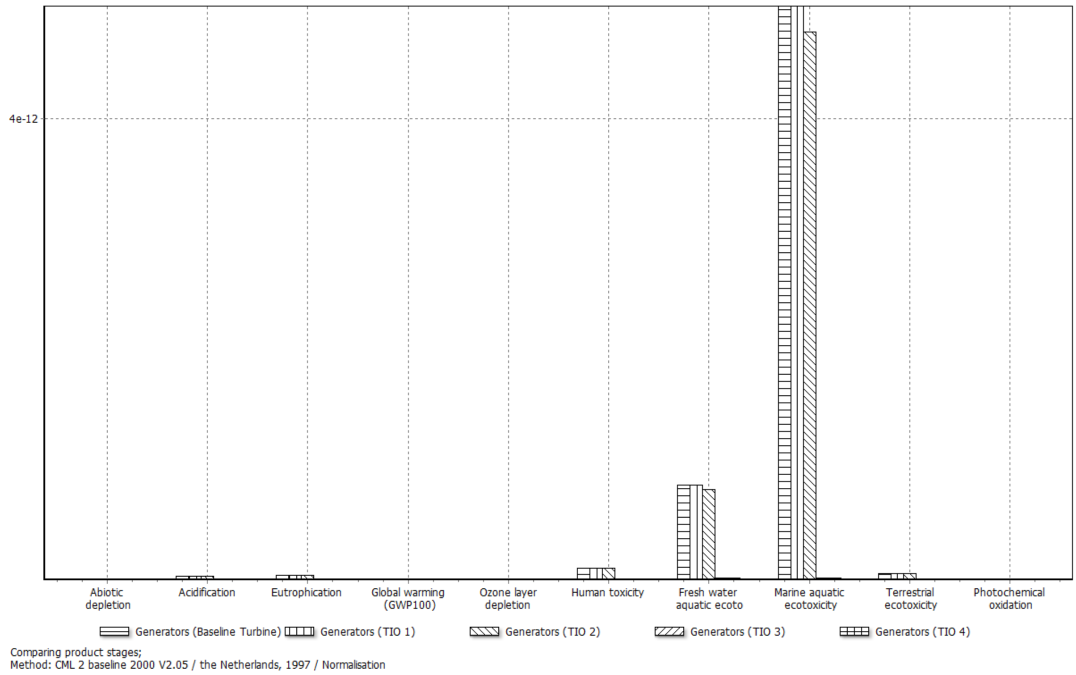


Figure B-10. Normalization results for the comparison between the generators of the baseline turbine and TIOs 1 - 4

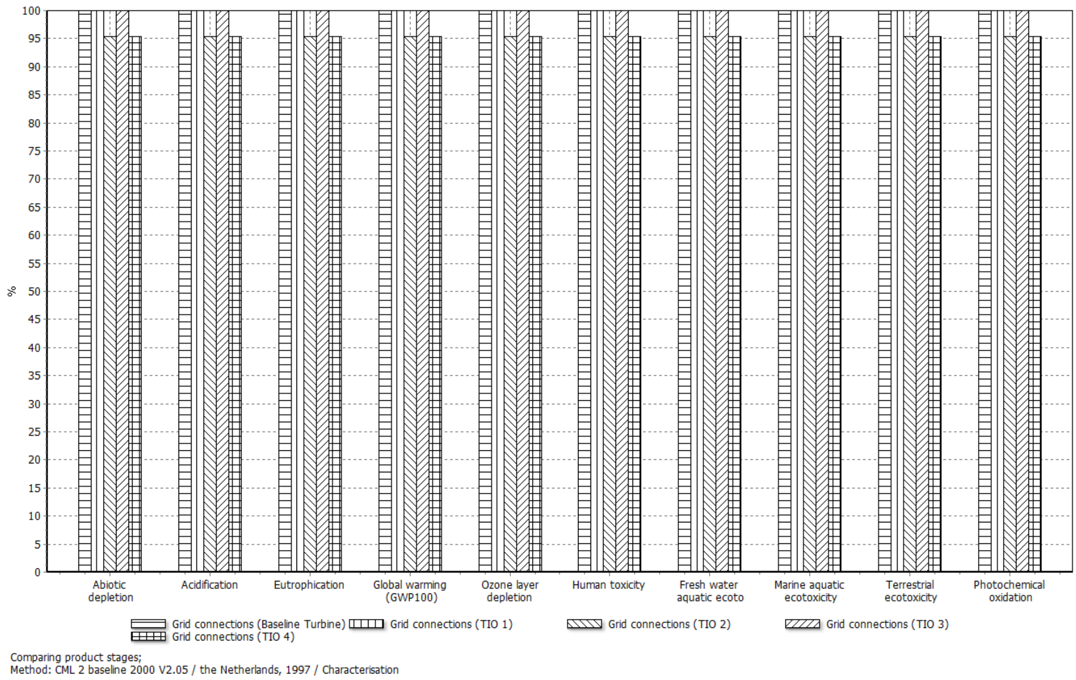


Figure B-11. Characterization results for the comparison between the grid connections of the baseline turbine and TIOs 1 - 4

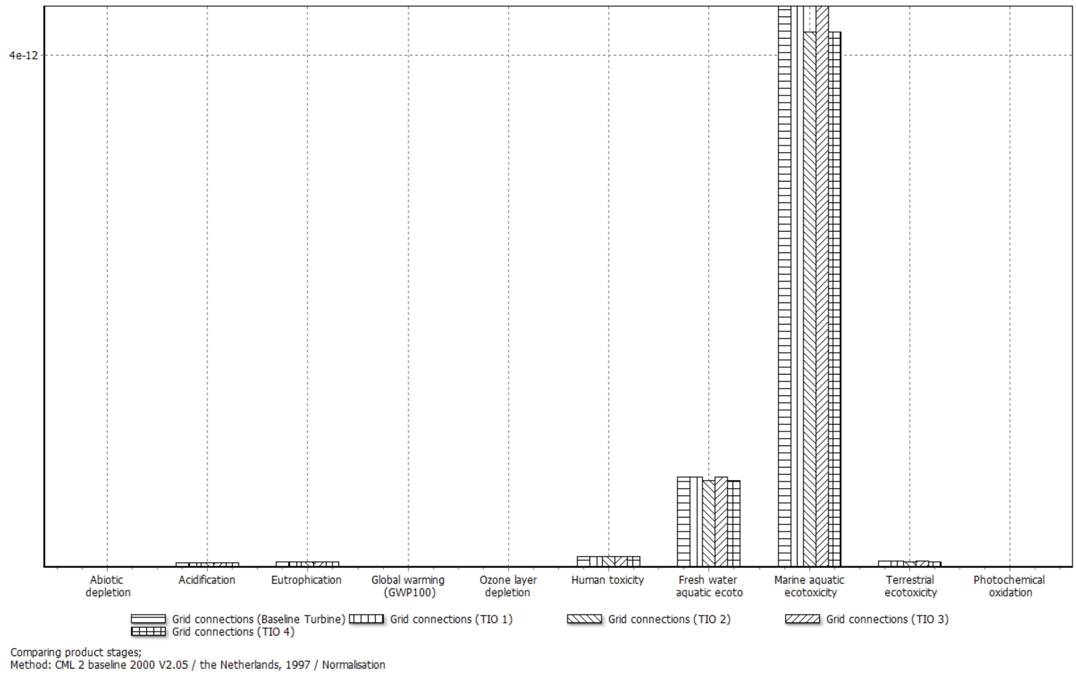


Figure B-12. Normalization results for the comparison between the grid connections of the baseline turbine and TIOs 1 - 4

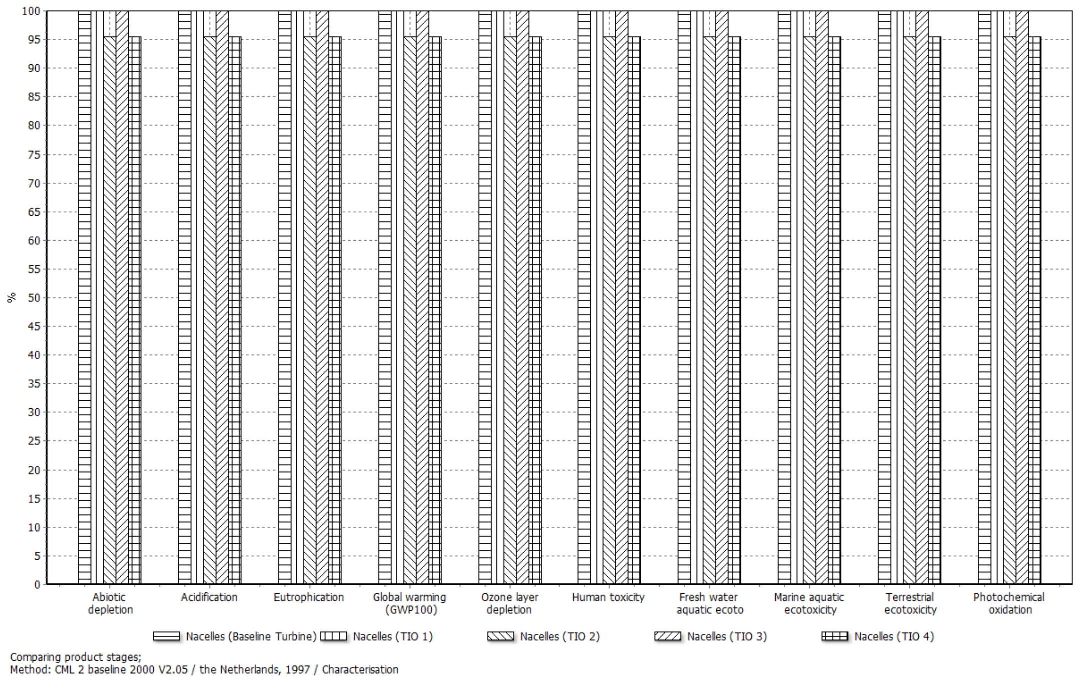


Figure B-13. Characterization results for the comparison between the nacelles of the baseline turbine and TIOs 1 - 4

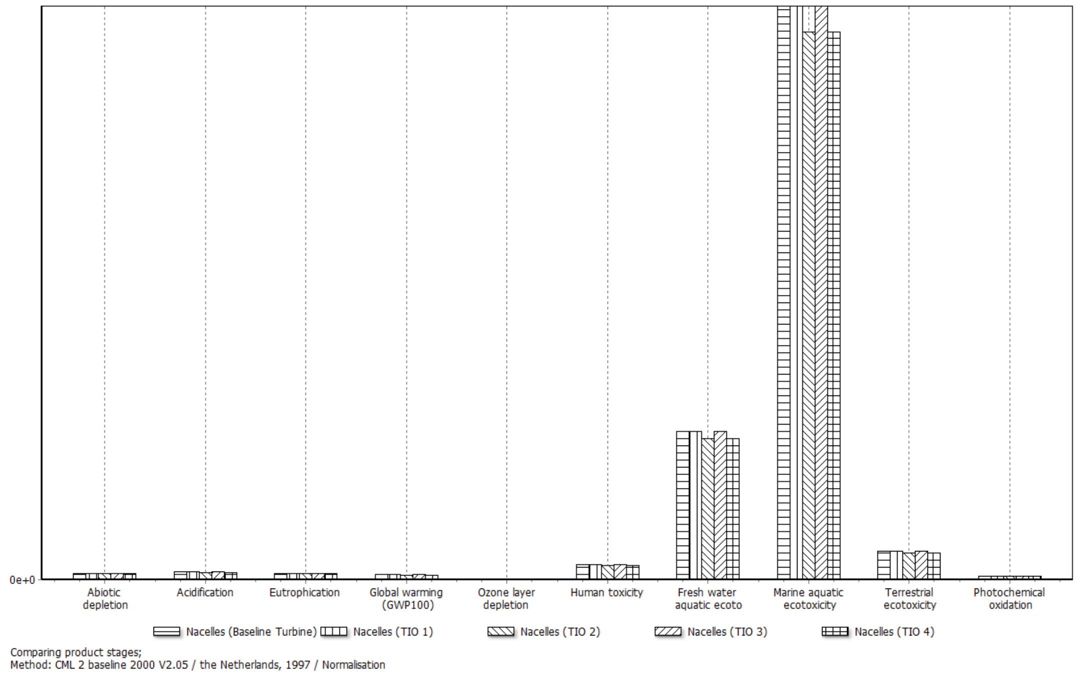


Figure B-14. Normalization results for the comparison between the nacelles of the baseline turbine and TIOs 1 - 4

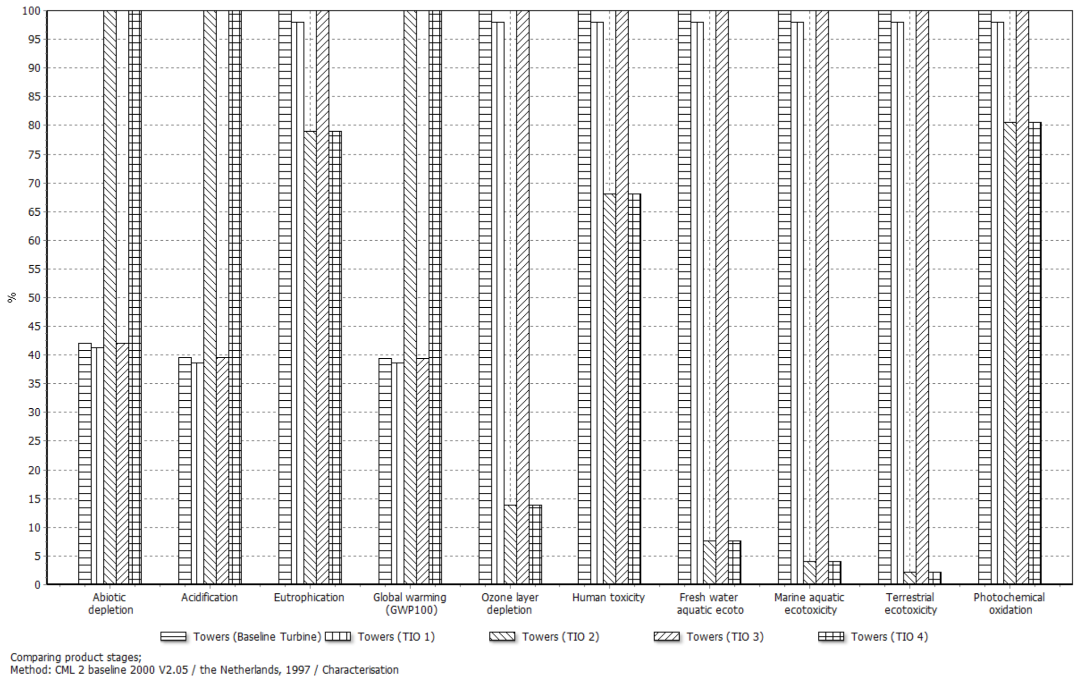


Figure B-15. Characterization results for the comparison between the towers of the baseline turbine and TIOs 1 - 4

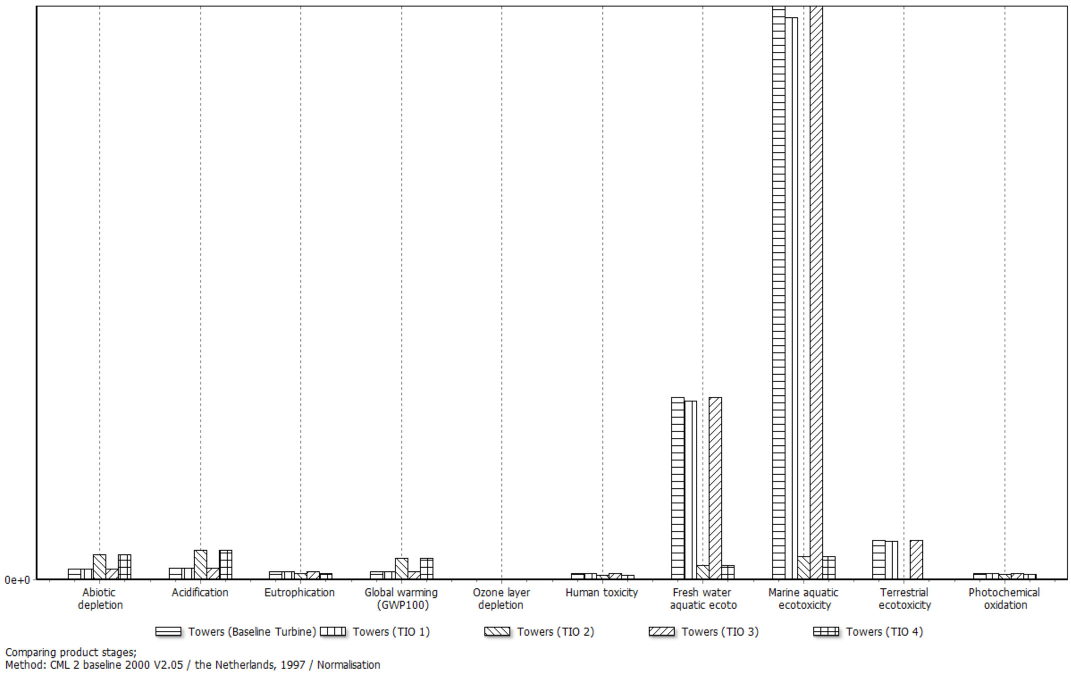


Figure B-16. Normalization results for the comparison between the towers of the baseline turbine and TIOs 1 - 4

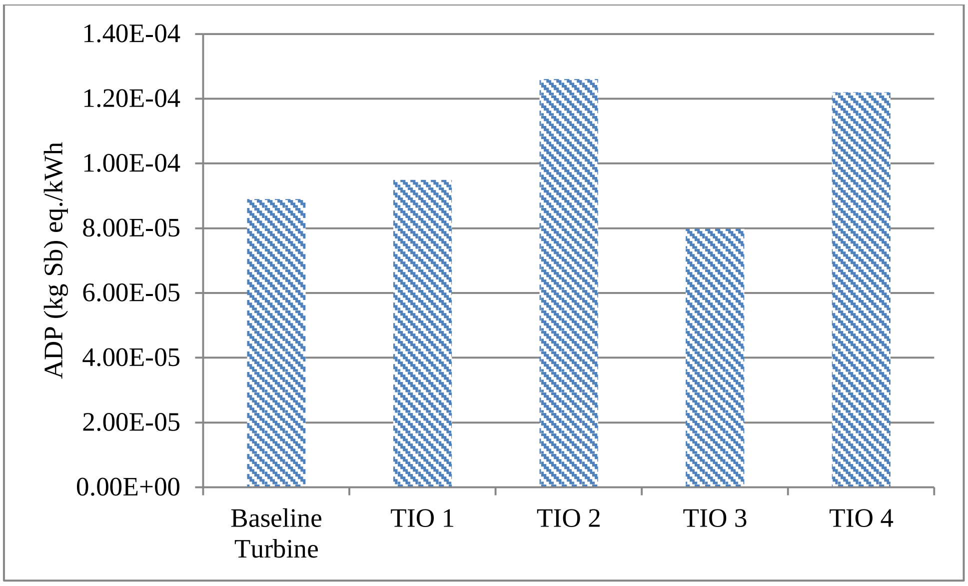


Figure B-17. Comparison of life cycle environmental impacts for ADP between the baseline turbine and TIOs 1 - 4

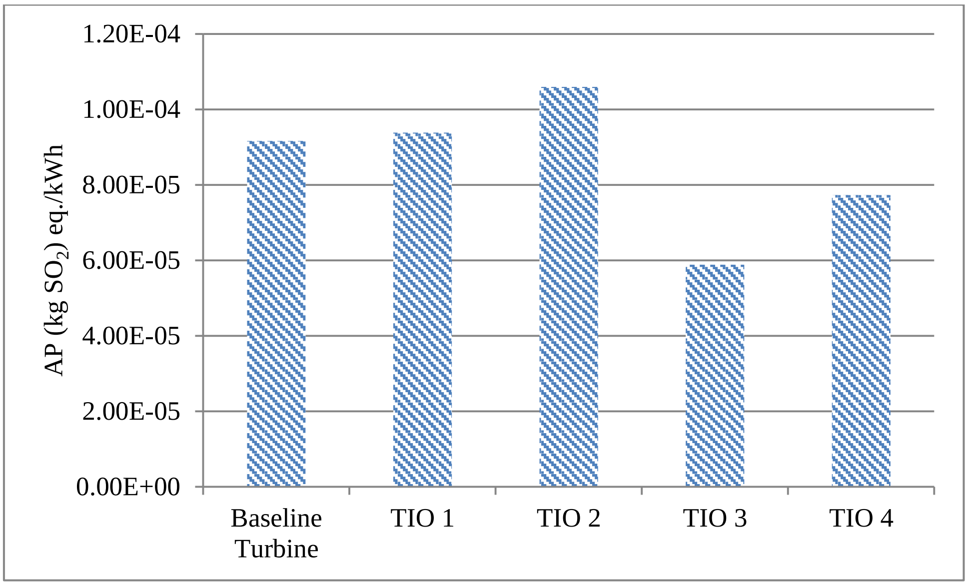


Figure B-18. Comparison of life cycle environmental impacts for AP between the baseline turbine and TIOs 1 - 4

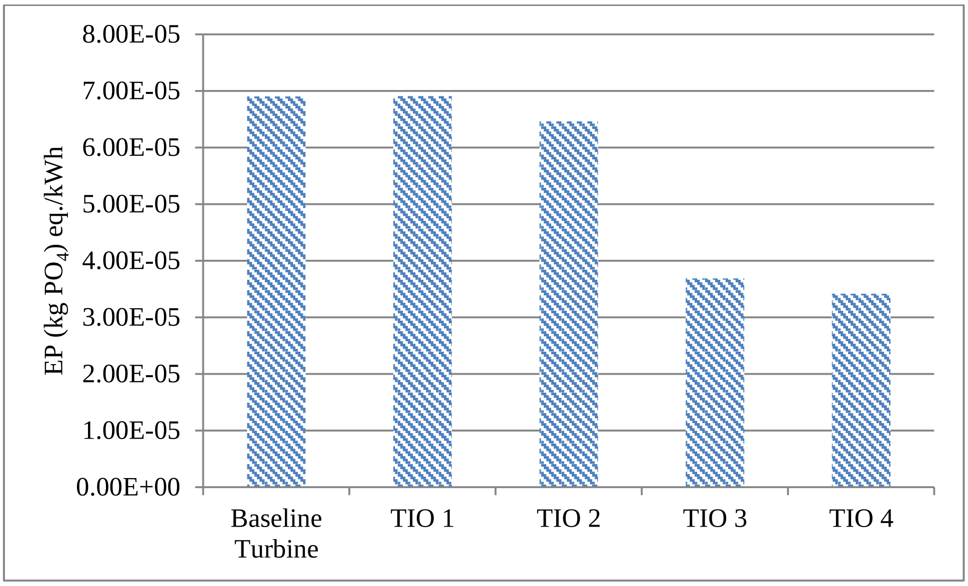


Figure B-19. Comparison of life cycle environmental impacts for EP between the baseline turbine and TIOs 1 - 4

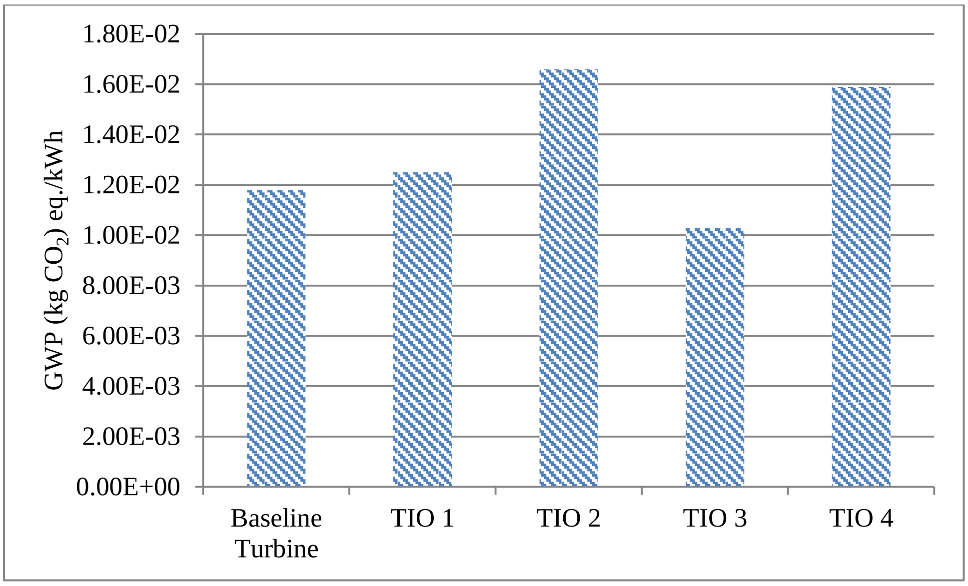


Figure B-20. Comparison of life cycle environmental impacts for GWP between the baseline turbine and TIOs 1 - 4

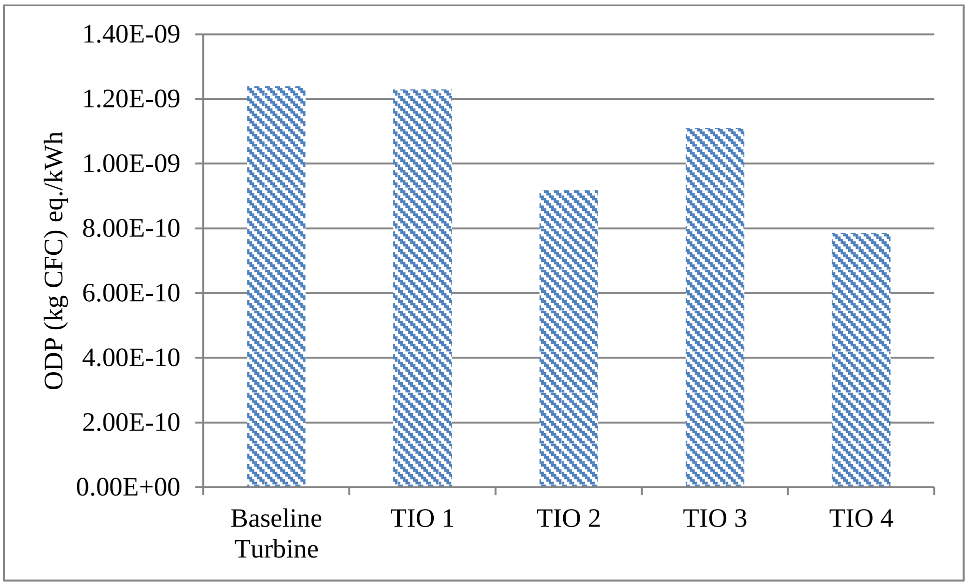


Figure B-21. Comparison of life cycle environmental impacts for ODP between the baseline turbine and TIOs 1 - 4

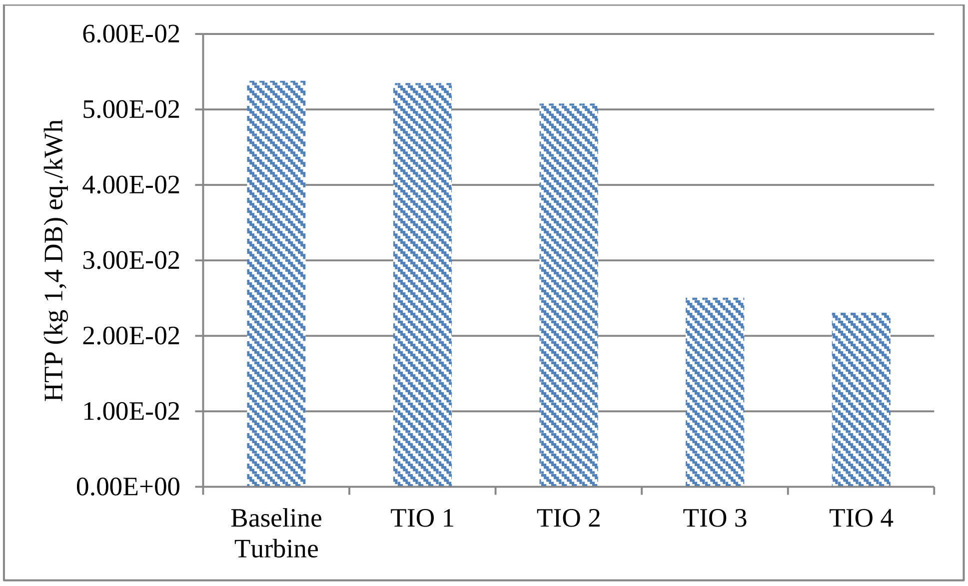


Figure B-22. Comparison of life cycle environmental impacts for HTP between the baseline turbine and TIOs 1 - 4

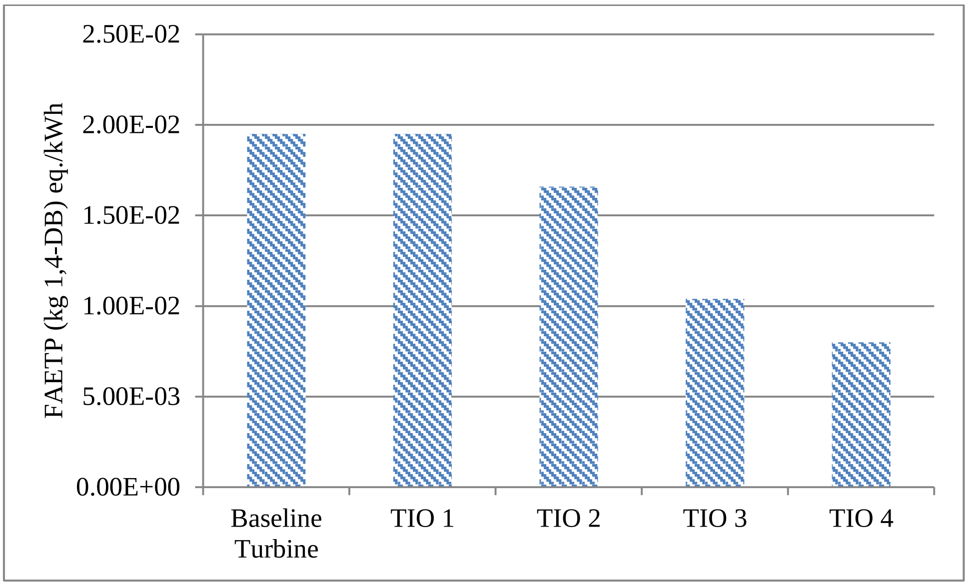


Figure B-23. Comparison of life cycle environmental impacts for FAETP between the baseline turbine and TIOs 1 - 4

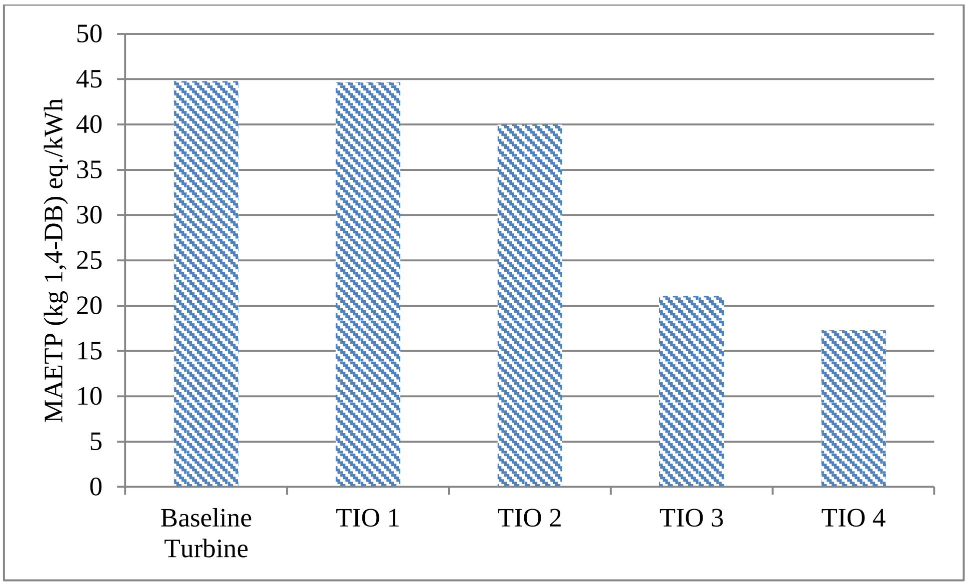


Figure B-24. Comparison of life cycle environmental impacts for MAETP between the baseline turbine and TIOs 1 - 4

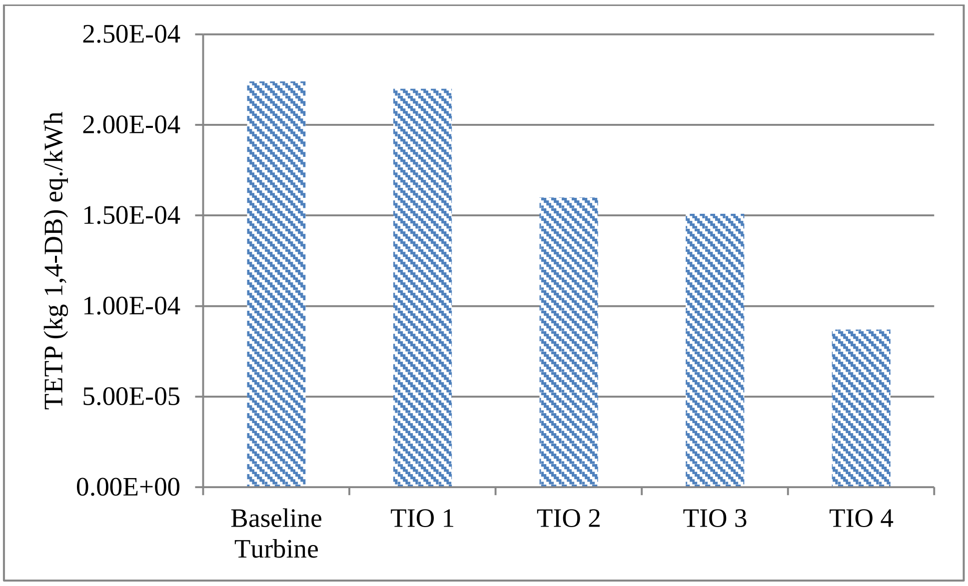


Figure B-25. Comparison of life cycle environmental impacts for TETP between the baseline turbine and TIOs 1 - 4

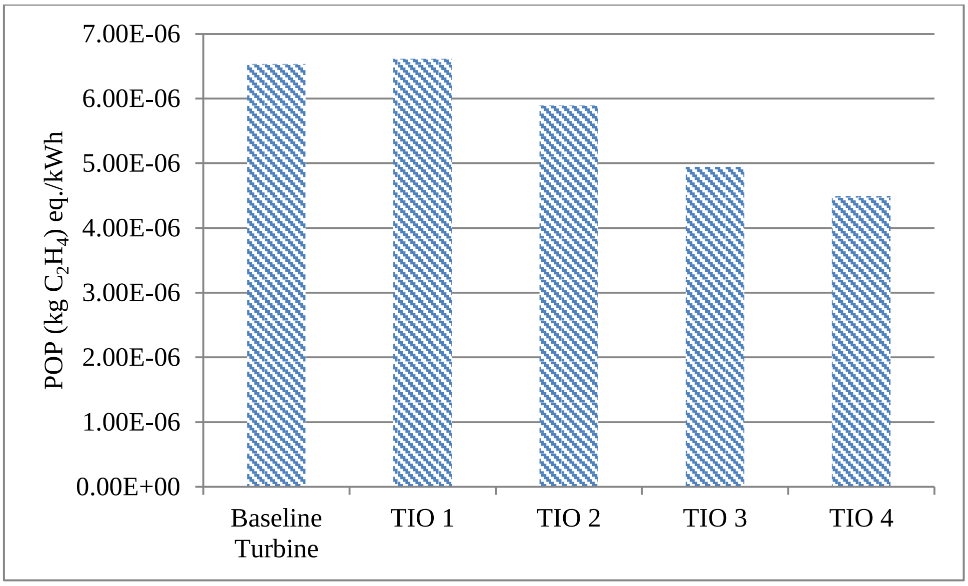


Figure B-26. Comparison of life cycle environmental impacts for POP between the baseline turbine and TIOs 1 - 4

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