Department of Mechanical and Aerospace Engineering

Technology-environment trade-off

in offshore wind farm development

Author: Diego López Gudiña

Supervisor: Dr Nick Kelly

A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2014

Copyright Declaration

Acknowledgements

First of all, I would like to express my gratitude to my supervisor Dr Nick Kelly, for the support and guidance that kept me focus to achieve the completion of this individual research. Sincere thanks to my course tutor Dr Paul Strachan for his advice and help provided throughout the whole academic year.

To Jacob, Javier, Miguel and Morna from Iberdrola – Scottish Power Renewables for their invaluable support and infinite patience they have shown when dealing with my sometimes naive questions.

To all the people I have met in this my first experience in Scotland, both inside and outside the university, that have made me aware of how important and powerful their support could be, even when the doubts seemed huge.

Last but not least, I would like to thank my family and girlfriend for always been there for me, no matter the distance or problems we faced and, for supporting me along this challenging and rewarding journey which would not have been possible without them.

Table of Contents

List of Abbreviations

AMSL	Above Mean Sea Level
CAPEX	Capital Expenditures
CO2	Carbon Dioxide
CRM	Collision Risk Model
dB	Decibel
DCO	Development Consent Order
EAOWL	East Anglia Offshore Wind Limited
EIA	Environmental Impact Assessment
ES	Environmental Statement
EWEA	The European Wind Energy Association
GHG	Green House Gasses
GW	Gigawatt
GWFL	Galloper Wind Farm Limited
GWh	Gigawatt-hour
HVAC	High-voltage Alternating Current
HVDC	High-voltage Direct Current
JNCC	Joint Nature Conservation Committee
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MW	Megawatt
MWh	Megawatt-hour
NnGOWL	Neart na Gaoithe Offshore Wind Limited
NOx	Nitrogen Oxides
NSIP	Nationally Significant Infrastructure Project

NTS	Non-Technical Summary
OWA	Carbon Trust Offshore Wind Accelerator
Pa	Pascal
PINS	Planning Inspectorate
SAC	Special Area of Conservation
SO2	Sulphur Oxides
SOSS	Strategic Ornithological Support Services
SPAs	Special Protection Areas
SPL	Sound Pressure Level
SSC	Suspended Sediment Concentrations
TCE	The Crown Estate
TLP	Tension Leg Platform
UXO	Unexploded Ordnance
Wspd	Wind Speed
WTG	Wind Turbine Generator

List of Figures

List of Tables

Abstract

Offshore wind farm development presents more constraints than only those related to technical specifications. This works aims to develop an understanding of the difficult balance between the environment and economic drivers for both developers and stakeholders.

Wind resource origin and evolution, from a technical and political point of view, will be put into context describing the main components of a wind farm development and their opportunities for improvement. With the help of technical and non-technical reports, made publicly available by the vast majority of the offshore developers, commissioned and future projects could be compared to try to forecast which would be the best wind turbine foundation combination in the years to come.

The main objective was to develop a methodology that could be used to discard at a very early stage some of those combinations while being at the same time easy to update and adapt to different scenarios. The core areas of the process consisted in a wind resource analysis, fundamental from an economic point of view and, a sea bird collision risk modelling as it has been always a consenting risk when dealing with onshore or offshore wind developments. To make the analysis more robust installation noise and loss of seabed impacts were addressed with the sector common practice approach.

An already commissioned project, from the Crown Estate Round 2 leasing stage was used to validate the method and point out any limitations. Applying the process to a depiction of the Round 3 to date consented projects allowed the prediction of the most suitable combination to be made. It could be concluded that suction bucket jacket is the foundation to choose and that wind turbine generators doubling in capacity the current ones would be the most suitable option. However the approach proved to be highly dependent on the quality of the data.

Chapter 1. Introduction

The present work summarizes the research and effort of the author to develop and test a high-level and easy to use methodology and evaluation rationale regarding offshore wind development.

1.1. Aim

Determine the best wind turbine and foundation combination for a theoretical UK location from a technical, economic and environmental perspective.

1.2. Objectives

The aim of this work will be addressed through the fulfilment of the following objectives:

1. Describe the main components of an offshore wind farm.
2. Summarize their most important technical parameters.
3. Evaluate those components regarding their most significant environmental impacts.
4. Establish the theoretical UK location parameters.
5. Analyse the different wind turbine option outputs.
6. Assess the different foundations associated impacts.
7. Determine the maximum likely capital costs.
8. Develop a matrix with weighted criteria to evaluate the different combinations.
9. Populate the matrix to determine the best solution.

1.3. Scope of Work

The present work is intended to address the non-straight forward decision making process involved in wind farm development with an special emphasis put into WTG and their foundations as they have a big impact in the initial capital investment. Different sources of information were available for the different parts of the analysis, from current papers and Environmental Statements to presentations and website articles. When possible peer reviewed journal articles were selected as they are claimed to be the most reliable source of information.

Several wind turbine generators (WTGs) ranging from output capacities from 2MW to a theoretical 20MW would be evaluated according to their economic and environmental impacts. At the same time there would be combined with different types of substructures foundations, taking also into account their associated environmental impacts, to try to determine the most suitable solution for a theoretical UK wind farm location. It should be noticed that the wind resource analysis would not take into account the dissimilarities derived from different WTG electrical components.

Wind energy resource estimation from different wind dataset sources with different time steps will be evaluated. Real data from meteorological monitoring stations and modelled data will be compared to assess how reliable this mathematical modelled sources are when trying to predict electricity generation from an offshore wind farm development with the best available dataset.

A levelised cost of energy analysis will be performed to obtain the capital investment limits that could be affordable for a wind farm developer. Furthermore as this type of projects do not only have technical constraints their environmental issues will be addressed. Ornithology, marine mammals and benthic fauna environmental related impacts will be analysed as they have proven to lead to high consenting risks.

It is not the purpose of this dissertation to address power losses derived from WTG components or from the transmission to the grid or analyse into detail wake losses derived from different wind farm layouts. Regarding the WTG substructure foundations the impact of the different soil conditions on the solution selection is out of the scope of the present work. Numerical approximations, when available, derived from the literature review would be used to try to reduce the impact on the final result.

1.4. Dissertation Structure

The present work is constituted by seven chapters that would address the following issues:

- Chapter 1 summarises the aim, objectives and scope of the present dissertation establishing the intentions and boundaries for this work.
- Chapter 2 provides an overview of the wind resource and the equipment necessary to extract power from it.
- Chapter 3 describes the Environmental Impacts associated with offshore wind development and the approach developers take to assess them termed Rochdale Envelope.
- Chapter 4 states the step by step process that was followed to obtain the results of the present work.
- Chapter 5 presents the outcomes of the application of the fore mentioned methodology.
- Chapter 6 contrasts previous results with an actual commissioned project and extrapolates Chapter 5 results to a theoretical Round 3 wind farm development.
- Chapter 7 shows the discussion and conclusions of the present work with a summary of possible areas for further work.

Chapter 2. Wind Resource

2.1. Offshore Wind Power

According to the Digest of United Kingdom energy statistics from 2013 the UK has the largest offshore wind resource in Europe due to its relatively shallow waters and strong winds (DECC 2013). In the recent years there has been a rapid development of the offshore wind energy sector with the UK raising its total installed capacity from 3GW to 4GW making it the worldwide leader (see Figure 1 Worldwide Offshore Wind Capacity 2013 (source lorc.dk).

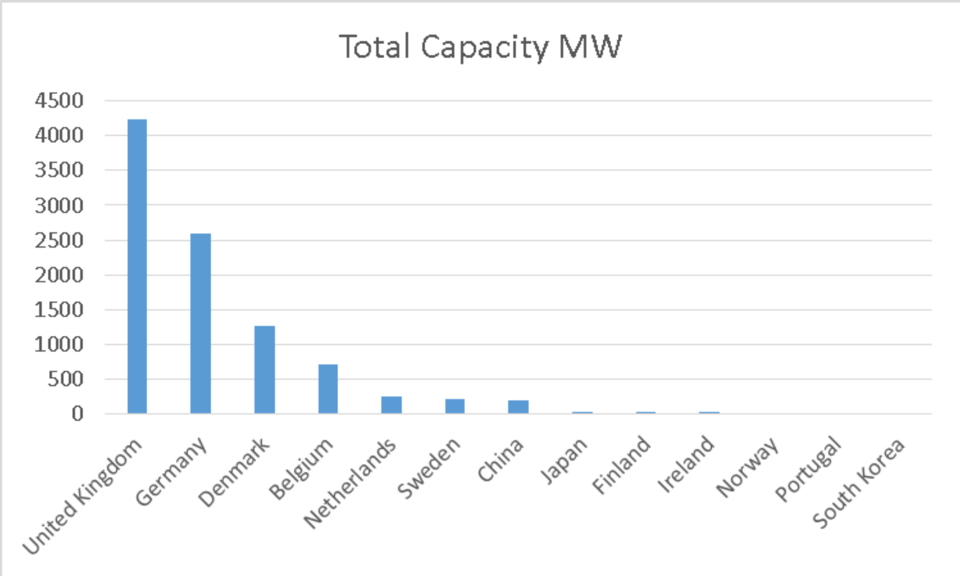


Figure 1 Worldwide Offshore Wind Capacity 2013 (source lorc.dk)

In the development of the UK's offshore wind capacity, the Crown Estate (TCE) have run several leasing rounds under which areas of the seabed have been made available for the development of offshore wind farms. Round 1 started in December 2000 and Round 2 in July 2003. In January 2010, the Crown Estate announced the successful development partners for each of the nine new Round 3 offshore wind zones, potentially totalling up to 33 GW in capacity. The Round 3 zones were identified through a combination of consultation with key national stakeholders and the Crown Estate's marine asset planning expertise. The Round 3 capacity is in addition to the 8 GW already enabled across Rounds 1 and 2. The combined total of all leasing rounds is over 49 GW (DECC 2013).

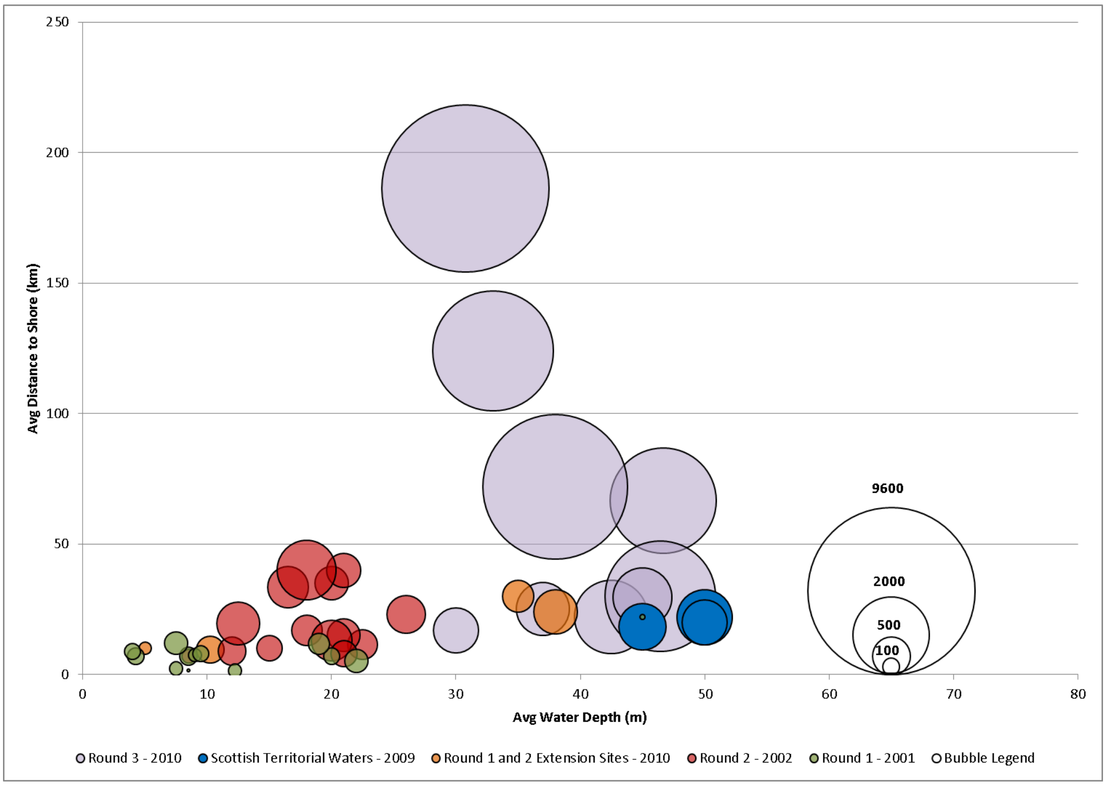


Figure 2 UK Offshore Wind Farm Development (source 4Coffshore)

We can see from the previous bubble graph that there is a trend to develop bigger wind farm far away from shore. This would lead to new technical and environmental challenges that will need to be addressed by both the developers and the consenting bodies. Several wind farm development projects have been withdrawn during the year 2014 contrasting with the announcement of what will become the world biggest offshore wind farm developed by Iberdrola Scottish Power Renewables in the area of East Anglia, formerly known as Norfolk (Infrastructure Planning 2014).

In the following table the most up to date TCE leasing rounds details have been summarised and will be used during the present work. There is a huge increase in the total installed capacity going from less than 2GW for the leasing Round 1 to more than 30GW in the current leasing Round 3.

Table 1 UK Offshore Wind Summary Figures (source RenewableUK)

Summary	Total Capacity MW	Avg Capacity MW	Avg Water Depth m	Distance to shore km
Round 1 - 2001	1188	91	14	8
Round 2 - 2002	6059	404	18	20
Round 3 - 2010	33380	1192	38	88
Round 1 and 2 Extension Sites - 2010	1301	325	22	18
Scottish Territorial Waters - 2009	2940	735	49	21

One of the biggest concerns arises from the high cost of energy associated with offshore wind. There is a target off achieving GBP100/MWh by 2020 but taking into account the current Round 2 costs situated around GBP150/MWh according to TCE there are serious concerns (Gellatly 2014) (The Crown Estate 2012). There will be a real need for both innovation and improvement of the ecnomy of scale th drive down costs.

2.2. Offshore and Onshore Similarities and Differences

It has been stated that offshore winds tend to blow at higher speeds and in a more consistent way than onshore land, mainly due to the absence of obstacles that could slow the wind, thus allowing turbines to produce more electricity. As a result, offshore turbines are generally larger than their onshore counterparts with the current commercially available turbines having a rated capacity of between 3 MW and 7 MW, although a number of larger, offshore specific, turbines are currently being developed.. Offshore development has claimed to benefit from less consent constraints such as planning, noise effects and visual impact and transportation of large components are reduced offshore (DECC 2013). According to the EWEA one of the major differences will be the complexity and cost of the substructures required for offshore wind turbines (EWEA 2011). Furthermore offshore maintenance and repair operations are much more expensive than the onshore ones mainly due to them being dependent on the weather conditions and vessel availability. It is not as easy to schedule maintenance works as it could seem for their onshore counterparts. From an environmental perspective there is not as much information available in order to assess and predict the potential impacts that an offshore wind development could cause in the marine environment. For example ornithology data is better known and monitored for onshore wind farm than for the offshore ones (Furness et al. 2013).

2.3. Wind Resource Assessment

Trying to find a practical location with steady winds is the main goal of what is known as wind resource assessment (Earnest 2013).

2.3.1. Weibull Probability Distribution Function

The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. Turbine designers need to know the type of environment that their turbines will be subjected to and so use statistical tools to try and predict wind distribution speeds. The probability of wind speeds at a prospective wind farm site can be modelled using a probability density function (pdf). For the purpose of the present work an analysis will be performed using this pdf to evaluate its performance when used to estimate the potential electricity generation for a particular location.

2.3.2. Wind Data Extrapolation

Wind data is normally obtained or simulated for a particular height that is usually different to the one at the hub height (see 2.4.1) that is going to be used for the estimation of the wind resource. An extrapolation is then needed to obtain the value. In order to extrapolate data that has been obtained at a particular height to the desired height several methods have been analysed. There were some concerns regarding the impacts of wind stability classes and wind extrapolated data (Newman & Klein 2014). The wind power law despite its simplicity was considered to have enough accuracy for the present analysis. It could be expressed as the following equation:

Equation 1 Wind power law

$$u(z) = u_{ref}\left(\frac{z}{z_{ref}}\right)^{p}$$

where $u(z)$ is the wind speed at height z, u_{ref} is the wind speed at height z_{ref} and p is the shear exponent. For the present work a shear exponent of 0.143 will be used representing neutral atmospheric conditions (Newman & Klein 2014).

2.3.3. Reanalysis Data

According to Brower (2013) the standard deviation of the annual mean speed over a representative number of years, also known as inter-annual variability, makes the measures from meteorological stations not suitable to estimate the production of surrounding wind farms. Reanalysis data is a new source of meteorological information that could offer a potential solution to this problem.

Numerical weather prediction model driven by historical weather observations from a wide range of sources such as satellites or balloons are used to produce this type of data sets. Brower (2013)stated that in order to provide a record as consistent as possible the model and data-assimilation system are “frozen” in time and only the observational data is allowed to change. This makes to generate synthesised weather records of gridded atmospheric variables such as temperature, pressure and wind amongst others (Brower 2013).

In the present work the Modern-Era Retrospective Analysis for Research and Applications (MERRA) will be used to estimate the electricity generation from a theoretical wind farm location.

2.4. Wind Farm Main Components

In this section special interest will be put in those components object of our study namely wind turbine generators (WTG) and their foundation substructures with the last having the biggest impact in the literature review due to their wide range of options.

2.4.1. Wind Turbine Generator

Its main function is to convert the kinetic energy from wind into electrical energy, typically connected to a generator in order to produce electricity. They are based in the old windmills concept and have been evolving since small devices to multi MW ones. Modern wind turbines are designed to operate throughout a range of wind speeds being able to change their blade angle to maintain a steady output electricity generation. There are three key concepts within this range termed cut-in speed, rated speed and cut-out speed. The cut- in speed refers to the minimum wind speed that the turbine requires to start generating electricity. On the other hand the rated speed is the wind speed at which the turbine is producing maximum power and finally the cut-out speed is the point at which the WTG is stop to avoid any potential damage in their components due to the wind being too strong.

2.4.2. Support Structure Foundations

A WTG support structure is the part that connects the WTG tower to the seabed while the foundation is the actual mode used to secure the structure to the seabed (de Vries 2007). As it has been already mentioned in section 2.2 offshore support structures are more costly and complex than their onshore counterparts.

When selecting a foundation type several considerations have to be taken into account being the most important, from a technical point of view, WTG characteristics, seabed conditions and water depth (EWEA 2011). Most of the current operating UK wind farms have monopile foundations

In the present work the word foundation will be used to refer to both the support structure and the foundation.

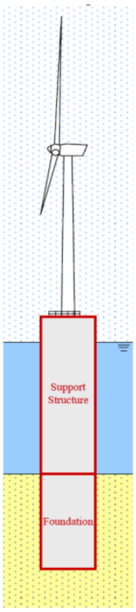


Figure 3 Support Structure Definition (de Vries 2007)

2.4.3. Offshore Substation Platforms

The Offshore Substation Platforms (OSP) are required to collect the electricity from the WTGs and transmit the power to shore at the most efficient voltage level and with the minimum number of transmission cables (Arcus Renewable Energy Consulting Ltd 2012).

2.4.4. Meteorological Monitoring Stations

Meteorological masts are required to monitor real time weather conditions within the wind farm and fundamental to obtain accurate wind data to evaluate the electricity production and to aid in the wind farm layout decision process. These details are then correlated and compared to the turbine performance to ensure that the most efficient and effective operation is being implemented (Arcus Renewable Energy Consulting Ltd 2012). Met mast are commonly used to test different types of foundations being the Horns Rev suction bucket foundation an example (Gellatly 2014).

2.5. Options For The Analysis

In this subsection the different options for the analysis will be presented with an extensive description made for the different types of structure foundations.

2.5.1. Wind Turbine Generator

Different wind turbine generators (WTGs) ranging from output capacities from 2MW to a theoretical 20MW would be evaluated in the present work and their main characteristics could be seen in the Table 5 and their power curves are located in Appendix I. Notice that in that graph the 20MW option was not represented to avoid distorting the graph.

2.5.2. Structure Foundations

As offshore wind is looking for economic solutions suitable for deeper water several foundations inspired by offshore oil and gas sector have been considered. Mainly because this sector has been developing those types of structures since 1970s building a broad experience on the matter (de Vries 2007). It has to be taken into account that the loads that offshore platforms have to withstand are very different than those for a WTG. According to Det Norske Veritas (2007) support structures could be categorised by their nature and configuration, method of installation, structural configuration and selection of their construction materials. These support structures can be divided into five basic types:

- Monopile or monotower
- Tripod
- Lattice or jacket
- Gravity
- Floating

If the foundation type is taken into account they could be:

- Piled
- Gravity-based
- Skirt and bucket
- Moored floating

Any water depth limits stated under these sections have to be considered as guidance rather than limitations. Theoretically any type of foundation could be built and installed at any depth with the adequate technology. To address this issue recommendations extracted from the literature review will be presented here.

A report by the European Wind Energy Association (EWEA) stated that monopile foundations have been used by the majority of the offshore wind farm developments built in water depths of under 25m due to their simple production, easy installation and cheaper cost. Gravity-based structures (GBS) make up most of the remainder with a small number of lattice or tripod structures have been installed so far (EWEA 2011).

The same report suggested that monopiles were expected to continue to be dominant up to the technical limits of their feasibility in terms of turbine size, water depth and ground conditions. GBS designs will also continue to capture a proportion of the market share within shallower and more sheltered sites. For deeper water sites, space-frame structures are expected to be the chosen design for the majority of developers as more challenging sites are developed (EWEA 2011).

To continue with the options that will be used for the present work analysis will be presented and described, providing when possible benefits and drawbacks of their use.

2.5.2.1. Monopile

A monopile foundation consists of a single steel or concrete reinforced pile which is embedded into the sea bed. It could be considered an extension of the onshore WTG tower below the sea surface and into the seabed. The maximum water depth and the WTG rated capacity determine how far the pile goes into the sea bed, its pile diameter and wall thickness (EWEA 2011).

It is stated as an advantageous solution in areas with movable seabed and scour (Det Norske Veritas 2007). Reports have stated that one of the disadvantages of the monopile is that is becomes less stable in deeper waters, and is best suited to water depths of up to 30 metres (Aagaard 2014). Such large diameters will be needed due to stiffness requirements that it will hardly unlikely to fabricate such a structure, due to limitations on the size of the steel plates that can be produced by steel mills and at the same time installation will arise due to limited sizes of pile driving equipment (de Vries 2007). It is possible however, that future improvements in manufacturing process and size of installation equipment will mean that monopile structures with very large diameters will be possible reducing its flexibility and making it suitable for deeper water sites of up to 60m with XXL monopiles (EWEA 2011)(A2SEA 2014).

2.5.2.2. Tripod

Consists in three-legged structure made of cylindrical steel tubes. Environmental and ground conditions will require the base width and the pile penetration depth to be adjusted. The piles in this case would be relatively small, say 2 to 3 m in diameter. As with monopile designs, the size of the multi-pod foundation will increase with the capacity of the turbine, but it will also be affected by wave conditions and water depth at the site. This type of structure is well suited for sites ranging in water depth from 20 to 50 m (EWEA 2011). When compared against the monopile it has a larger overturning resistance and it could be shallower and lighter. However, much effort is required in the design and engineer stage to address the fatigue problems related to the complex element that main joint is. Besides the triple leg configuration makes directionality of wind and wave loads more of an issue and it cannot be transported as easily as a monopile (de Vries 2007).

2.5.2.3. Jacket Piled

A jacket structure is made up usually of four legs connected by slender braces, making it a highly transparent structure with the term 'jacket' having its origin in the oil and gas industry as it was used to indicate a space frame structure which had the piles driven through the legs (de Vries 2007). It has a large resistance to overturning due to its large base. Despite the fact that the space frame structure allows for light and efficient construction with significant material savings it has been stated that due to each of the joints having to be specially fabricated, and therefore many man-hours of welding being required it is an expensive type of foundation (EWEA 2011) (de Vries 2007). Furthermore, transportation will be an issue, particularly when installing a large number of turbines.

There are several examples of offshore wind developments that have used jackets foundations such as: the Beatrice Demonstrator (2006) where two 5 MW turbines are installed on jackets in 45 m water depth, Alpha Ventus (2009), Thornton Bank (2011) and Ormonde (2011) wind farm projects although they have been commonly employed in the offshore oil & gas sector for many decades (EWEA 2011).

2.5.2.4. Jacket Suction

This type of foundation consists of three legs welded together in a jacket structure, standing on top of three giant suction buckets anchoring the foundation to the seabed. It is a lightweight structure that benefits from negligible noise emission and shorter times of installation decreasing the impact on the marine environment (Carbon Trust 2014). It is claimed to be suitable for water depth up to 60m. It has been developed by DONG Energy in cooperation with Carbon Trust Offshore Wind Accelerator (OWA) in the UK.

The German offshore wind project Borkum Riffgrund 1 in Germany has been selected for testing this foundation due to its sandy seabed, which makes the installation of this concept a challenge. It is expected that in October of 2014, a 3.6MW WTG will be installed on top of the foundation (DONG Energy 2014).

2.5.2.5. Gravity Base Structure (GBS)

A Gravity Base Structure (GBS) relies on a low centre of gravity combined with a large base to resist overturning. Due to a large mass been required it is generally made of concrete as it is much cheaper than steel. Once installed in the correct location, they need to be filled with ballast material such as pumped sand, concrete, rock or iron to increase their weight. When the environmental loads are low and ballast material can be provided at a modest cost they are a competitive solution (EWEA 2011). No separate transition piece needs to be installed if the GBS is extended to the platform level (de Vries 2007).

To date, cylindrical or conical reinforced concrete caissons GBSs have been used in offshore wind projects with the drawback that they need extensive seabed preparation and scour protection to prevent erosion around the base. It is expected that the dimensions of GBS will increase with turbine capacity, the site wave conditions and water depth. This type of structure is currently suited for sites in water depths up to 30 metres even though it could be considered for deeper sites. To date these designs have been used in many of the offshore wind projects such as Lillgrund in Sweden and

Rødsand in Denmark, where water depths and meteorological and oceanographic, also known as metocean conditions are suitable (EWEA 2011).

2.5.2.6. Inward Battered Guide Structure (IBGS)

It consist of a vertical central pile or caisson that is driven into the seabed with a prefabricated pile guide structure placed and grouted into position over the caisson. Battered (inclined) piles include a reinforced concrete pile cap sitting on battered driven steel piles. It is suitable only for shallow, well sheltered waters (EWEA 2011). Benefits deriving from the use of this type of foundation are cheaper costs of fabrication and installation. It needs 20% less steel than a jacket, with fewer welds and due to its reduce size more units could be carried per installation vessel (de Villiers 2012).

This foundation has been successfully installed to support a meteorological mast in the Hornsea area in 2011, located 100km from shore and in a water depth of 30m (Gellatly 2014).

2.5.2.7. Suction Bucket

The suction bucket, also known as suction caisson foundation, is essentially a monotower with a large diameter cylinder with a closed top. Its installation starts by placing it on the seabed and subsequently removing the water from the interior of the suction bucket with a pump, creating a pressure difference with respect to the ambient pressure, which results in a downward force. Therefore the suction bucket is pressed down into the soil (de Vries 2007). This concept is not suitable for very shallow waters due to its reliance on the pressure difference for its installation and its recommended for depths up to 25m (Det Norske Veritas 2007). The need for pile driving and associated noise are avoided with this type of foundation. However, suction buckets are limited to use in relatively uniform benign soils and hence are unsuitable for many European sites (EWEA 2011). It presents the benefits of the suction operation being able to be reversed allowing the complete removal of the foundation.

This foundation has been successfully installed to support a meteorological mast in the Dogger Bank area in 2013, located 150km from shore and in a water depth of 25m (Gellatly 2014).

2.5.2.8. Floating

To date seabed mounted or “fixed” foundation concepts have been utilised in all commercial scale offshore wind farm developments. But this trend could change due to the fact that many countries have scarce shallow water locations suitable enough to allow economically viable developments. Just in Europe Norway and much of the Mediterranean and Atlantic basins face this difficulty (EWEA 2011). Within water of depths over 50m is where floating support structures are likely to be a more economical solution. They present key benefits due to their flexibility in the commissioning and decommissioning phases and they are claimed to be the sole option available for depths over 70m (Wilhelmsson et al. 2010). Every floating foundation relies on buoyancy to keep the WTG above the water (de Vries 2007). In this section three types will be described: barge floater; tension leg platform and; spar floater.

2.5.2.8.1. Barge Floater

The oil and gas industry has provided different configurations where the WTG could be placed on a barge and then attached to the seabed with anchor lines that could be either catenary or taut. Driven piles, drag or suction anchors could be used to complete the mooring (de Vries 2007). This type of foundation present the benefit of allowing the WTG to be assembled at an onshore location reducing the need for large jack-up vessels. This concept is claimed to be suitable for large scale production as it can be easily adapted to different water depths and towed out to the required location after assembly takes place. As a drawback it would require a certain water depth, over 40m, for the mooring concept to be applied and it is highly sensitive to hydrodynamic loads (Principle 2013)(de Vries 2007). Furthermore this type of foundation has extensive footprint when compared against other floating structures (Pelastar 2013).

2.5.2.8.2. Tension Leg Platform (TLP)

Another option for a floating structure is a Tension Leg Platform (TLP), which is tethered to the seabed by means of pre-tensioned cables in water depths ranging from 50m to 500m (Pelastar 2013). A template can be used to fix the cables on the seabed or to individual piles or suction buckets (de Vries 2007). Presents the benefit of allowing the installation and maintenance to be very simple when compared with other options as it could be towed to the desired location with the WTG already attached (Det Norske

Veritas 2007). It is claimed to have a compact footprint and a minimum impact on the seabed (Pelastar 2013).

2.5.2.8.3. Spar Floater

This foundation obtains its buoyancy from a cylinder that protrudes below the water line. This cylindrical body is generally long and with a minimized cross section reducing the wave induced motion. Chains in a catenary shape could be used to anchor it to the seabed. The need for large draft to ensure buoyancy could lead to problems in shallow waters making this design not very cost effective in those situations (de Vries 2007). According to EWEA from this three floating foundation only the spar has been demonstrated at full size offshore (EWEA 2011).

2.5.2.1. Foundations Suitability

There is no clear procedure to address determine the foundation that suit ever situation. This process is very site specific and dependent on a high number of variables. In order to try to simplify this issues a foundation suitability matrix from the literature review will be described in this section. It consist on an expert judgement evaluation of all the foundation options considered for this analysis and even provides a comparison with the floating devices.

This analysis has taken into account different parameters spread over several categories that tried to depict the different phases in the life cycle of an offshore wind farm development. In order to do this several categories were establish: site; design; fabrication; installation; maintenance; decommissioning and overall. This last one taking into account the reliability of the concept in terms of whether or not a concept could be viewed as proven technology. The relative importance of the parameters was established by assigning weights to each of the parameters. Four different water depths were assumed namely: 30m, 45m, 80m and 120m. An evaluation matrix was created using a spreadsheet program and then was distributed among several experts for ranging each parameter with a score from 1 to 10. The results were collected and processed as part of the Upwind project (de Vries 2007). A version adapted for this present work could be seen below.

Table 2 Averaged Score per Foundation Type (adapted from (de Vries 2007))

Water Depth (m)	Monopile	Tripod	Jacket	Gravity Base	Suction Bucket	Floating Barge	Floating TLP	Floating Spar
30	961	861	861	826	799	748	669	626
45	794	843	855	791	721	756	676	761
80	628	772	817	717	603	785	711	808
120	519	714	822	736	593	900	803	944

This preliminary results stated that monopile scored progressively worse for increasing water depth while jacket score was relatively constant and floating structures performed best in deeper waters as could be expected from the literature review (see 2.5.2). It was stated that as this was the first iteration there could be modifications as more knowledge and insight have been gained by the offshore wind sector (de Vries 2007).

It has to be taken into account that from the group of experts there were concerns on how difficult it was to assess the effect of increasing water depth for certain parameters (de Vries 2007).

From the previous analysis performed within the Upwind project several regression methods were realised to obtain equations for each type of foundation. These equations could be used to estimate the suitability of each type of foundation taking into account some parameters that were out of the scope of the present work.

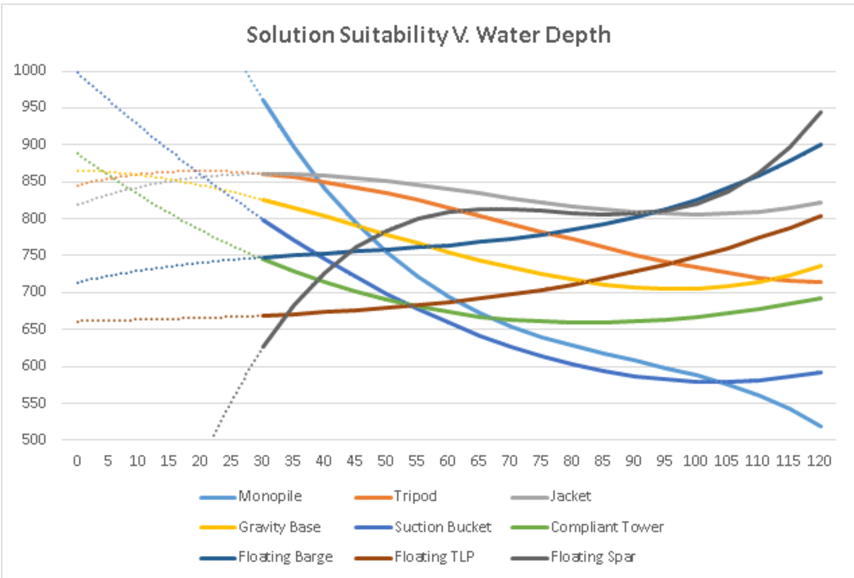


Figure 4 Foundation Suitability Regressions (modified from (de Vries 2007))

Chapter 3. Environmental Impacts of Offshore Wind

Under European legislation, transposed into UK law certain projects are required to undertake an Environmental Impact Assessment (EIA) to identify and reduce potential impacts arising as a result of the development. The output of the EIA process is the Environmental Statement (ES), a document that is provided to the consenting authority, in this case the Planning Inspectorate, in support of the consent application for the onshore and offshore works. Those ESs were used in the present work to obtain some technical parameters and delimitate the boundaries of the analysis.

3.1. Principles of Environmental Impact Assessment

The emergence of Environmental Impact Assessment (EIA) as a key component of environmental management over the last 40 years has coincided with the increasing recognition of the nature, scale and implications of environmental change brought about by human actions. During that time, EIA has developed and changed, influenced by the changing needs of decision-makers and the decision-making process, and by the experience of practice (Morgan 1998).

According to the International Association for Impact Assessment (IAIA and IEA 1999) the term EIA refers to the 'process of identifying, predicting, evaluating and mitigating the effects of development proposals prior to major decisions being taken and commitments made'.

The early literature on EIA (in the 1970s) sometimes was equivocal on whether 'environment' meant only the biophysical (or natural) environment. How-ever, by the 1990s, the normative literature on EIA generally used the term 'environment' in a broad sense, and EIAs were meant to include all non-monetary impacts (i.e., impacts not included in a benefit-cost analysis). EIA is often narrowly focused on biophysical impacts, in part due to the fact that social impacts and other non-biophysical effects are not fully included in environmental impact assessment legislation (Ortolano & Shepherd 1995).

In the context of the present work every offshore wind farm development with a capacity over 100MW is considered a Nationally Significant Infrastructure Project (NSIP) according to The Planning Act 2008. This serves as a framework where the EIA Infrastructure Planning Regulations 2009 No. 2263, that are the transposition of the EU

Directive 85/337/EEC, as amended by Directive 97/11/EC and 2003/35/EC, have to be applied. This means that an EIA is mandatory for this type of developments.

Most developers describe the EIA as an iterative tool that serves for assessing and examining the impacts and effects during the lifetime of a project on the environment in a systematic manner (GWFL 2011a).

It is important to establish a differentiation between the terms “effects” and “impacts”. Effects are physical changes, usually measurable, to the environmental baseline conditions as a result of a particular project aspect (GWFL 2011a). Impacts are changes that are judged to have environmental, political, economic or social significance to society. Impacts may be positive or negative and may affect the environment, communities, human health and well-being, desired sustainability objectives, or a combination of these (IAIA and IEA 1999).

From the review of several ES most developers agree that the EIA consists in the following stages:

- **Project Concept**. Outline of the need for the development and its characteristics.
- **Screening**. Determine whether the development needs an EIA or not.
- **Scoping**. Establish which issues should be addressed in the EIA and which could be discarded.
- **Impact Assessment**. Identify and evaluate potential impacts. Data is collected and surveys undertaken to establish the baseline conditions to compare against. Mitigation measures and long term monitoring regimes determined if necessary.
- Completion of **ES** and submission of application.
- **Consultation**. All along the process stakeholders engagement is developed to use their feedback to shape and guide the impact assessment process and even influence the output by changing the project characteristics.

The emphasis should be on prevention rather than on mitigation or restitution, and feedback and interaction should link each step (Mainstream Renewable Power 2012).

A diagram could be seen below that represents these stages as an iterative process (see Figure 5).

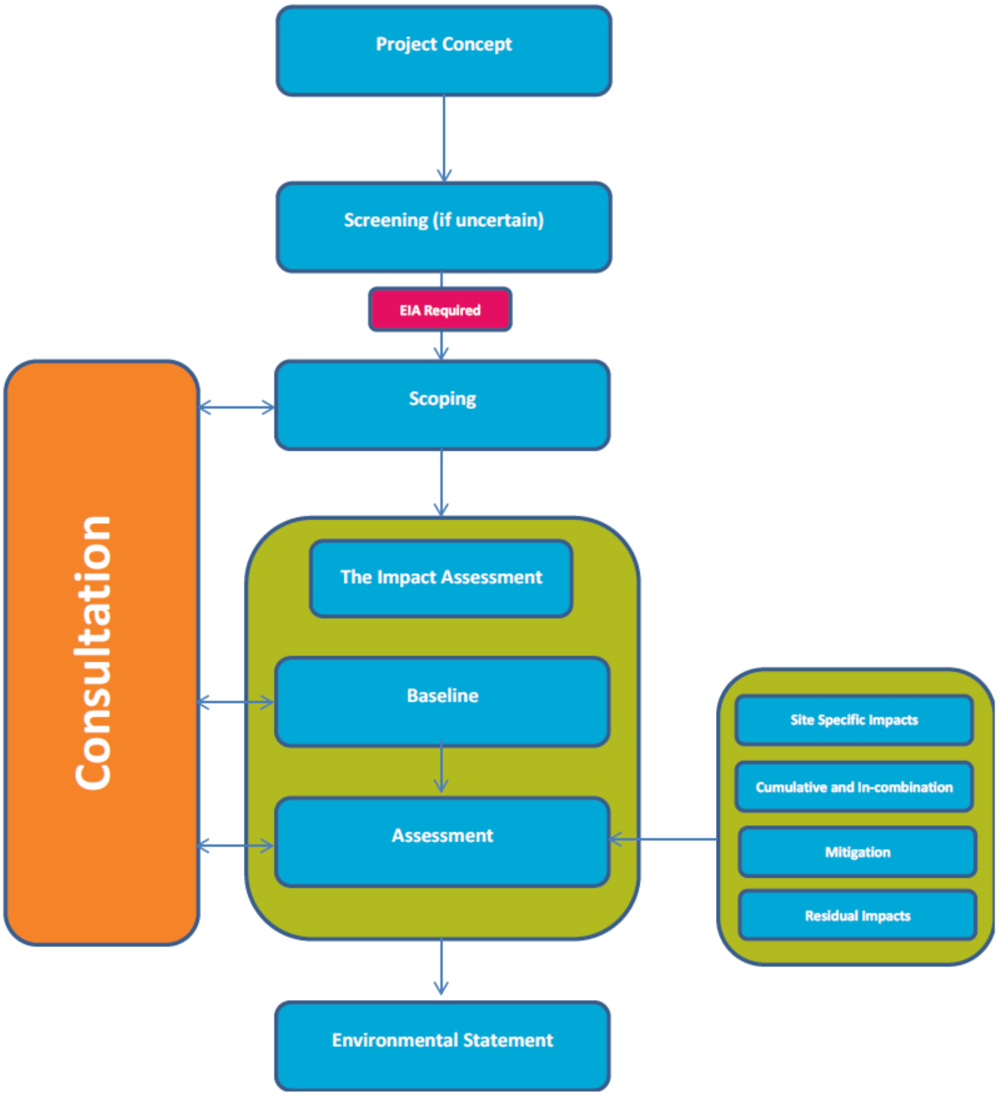


Figure 5 EIA Stages (Mainstream Renewable Power 2012)

3.1.1. Impact Assessment Methodology

The "source-pathway-receptor" model is commonly used to define those sensitive receptors that should be considered at risk. "Source" is considered to be the origin of a potential impact, "pathway" is used to refer to the means by which the effect of the activity could impact a "receptor" and, "receptor" is stated to describe the element within the receiving environment that is impacted (GWFL 2011a). Notice that when there is no "pathway" no impact is considered to occur and therefore the effect could be screened-out (see Figure 6).

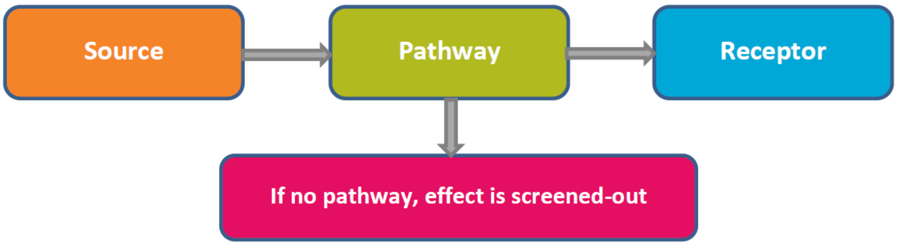


Figure 6 Source-Pathway-Receptor Model (Mainstream Renewable Power 2012)

A differentiation between impact and effect has already been provided (see section 3.1). But in order to estimate and categorise those impacts it is needed to describe a few more concepts namely: type and magnitude of impact, receptor vulnerability and impact significance.

3.1.1.1. Type of Impact

Impacts could be classified into:

- **Direct** impacts. Those caused by physical changes due to any phase of the project lifetime.
- **Indirect** impacts. Those resulting from a direct impact and may be experienced by a receptor that is removed (in space or time) from the direct impact.
- **Cumulative** impacts. Those that could be categorised as:
  - Inter-relationship impacts. When a single receptor suffers changes due to multiple sources and pathways.
  - Cumulative *per se*. Those derived from the interaction of several developments of the same type.
  - In-combination impacts. Those resultant from the interaction of the development and other offshore activities, both temporally and spatially.

3.1.1.2. Magnitude of Impact

It is the quantification of the impact itself and ranges from no change to high. Magnitude refers to the “size” of an impact. It is function of other aspects such as:

- **Spatial extent** of the impact. Refers to the geographic area of influence where the effect is noticeable against background variability. It could be either small scale or large scale.

- **Duration** of the impact. Refers to the temporal extent of the effect prior to recovery or replacement of the resource or feature. It could be either short term or long term.
- **Frequency** of the impact. How often the effect occurs. It could be from negligible to high.
- **Severity** of the impact. Measures the degree of change. It could be from negligible to high.

3.1.1.3. Receptor Value and Sensitivity

It refers to the susceptibility of a receptor to a change in baseline conditions and is a function of its capacity to accommodate the proposed form of change and would reflect its capacity to recover if it is affected (GWFL 2011a). It could be quantified, from negligible to very high, taking into account the receptor´s:

- **Adaptability**. Describes the ability of a receptor to avoid or adapt to an effect. In this case very high adaptability results in low vulnerability.
- **Tolerance**. Refers to how affected a receptor is by an effect. It could be affected or unaffected, either temporarily or permanently, with very high tolerance leading to low vulnerability.
- **Recoverability**. Describes how well a receptor recovers after having been exposed to an effect. In this case very high recoverability results in low vulnerability.
- **Value**. Refers to the scale of importance, rarity and worth. Very high value translates into high vulnerability.

3.1.1.4. Impact Significance

After the receptor value and sensitivity have been identified and the magnitude of the effect quantified an Impact Assessment Matrix (see Table 3) could be created to describe the significance the impact. It ranges from severe to no change. This methodology has proven to be a consistent framework for evaluating impacts for most of the ES reviewed. Impacts over different parts of the environment could be then compared against each other, in a qualitative manner, when using this assessment matrix. Ensuring that the decision-making process has all the information it needs to emit a based judgement. But not everything could be assessed at the early stage of the developments and therefore a balanced and flexible approach is needed. Here the need for the Rochdale Envelope raises as it could be seen in section 3.2.

Table 3 Impact Assessment Matrix (modified from (GWFL 2011))

Value / Sensitivity of Receptor	Magnitude of Impact				
	High	**Medium**	**Low**	**Negligible**	**No Change**
Very High	Severe	Major	Moderate	Minor	No Change
High	Major	Moderate	Minor	Minor	No Change
Medium	Moderate	Minor	Minor	Negligible	No Change
Low	Minor	Minor	Negligible	Negligible	No Change
Negligible	Minor	Negligible	Negligible	No Change	No Change

3.1.1.5. Mitigation and Residual Impacts

Developers use different means to remove, reduce or manage the fore mentioned impacts. This is what is called "mitigation" and is normally used where potentially significant adverse impacts have been identified. It forms part of every stage of the project since the inception until the decommission phase. In the reviewed ESs impact significance were provided before and after considering the mitigation measures. When those measures have been taken into account the value obtained is what is considered the "residual" impact. That impact has to be low enough to consider the mitigation measures successful.

As it has been described within this last section all changes to baseline conditions occurring above background environmental variation must be evaluated and assessed within the potential impacts caused by the development (Mainstream Renewable Power 2012). Notice that those impacts could be either negative or positive and have to be measured in terms of their significance. This significance is a function of both the vulnerability of the receptor and the magnitude of the impact. There is no common criteria when comes to which significance level should lead to mitigation measures. Some developers consider that from minor to major while others only consider from moderate to major. There is an agreement that severe impacts must be avoided.

3.2. The Rochdale Envelope Approach

The “Rochdale Envelope” comes from two legal cases: R. v Rochdale MBC ex parte Milne (No. 1) and R. v Rochdale MBC ex parte Tew [1999] and R. v Rochdale MBC ex parte Milne (No. 2) [2000], derived from a proposed business park planning application in Rochdale (TCE 2012). The initial planning application was claimed to provide an illustrative plan with not enough evidence and the original decision to issue consent was invalidated. Developers submitted after that decision a revised application with an EIA carried out within the limits of a project schedule and illustrations with the proposed parameters. An extended ES that was included in the revised application was challenged again but in that case the court decided that due to the ES had “assessed the likely significant effects of the development, based on details which were tied to the planning permission by conditions” (Rochdale MBC ex parte TEW [1999], Milne [2000]) it was adequate. Therefore for any planning application to be granted permission sufficient detail of the proposed project is needed to facilitate a robust EIA that has assessed all potential impacts. This design envelope allows developers to have some flexibility while their impacts evaluated in their ES are still captured within that envelope and therefore their EIA is still valid. From a “realistic worst case” perspective if no significant impact is demonstrated for that scenario it could be considered that no significant impact is likely for any scenario.

As most of the reviewed ES are for projects from England and Wales guidance notes from the Planning Inspectorate (PINS) would be described. Regarding the Rochdale Envelope the Advice Note 9 establish the key propositions:

- The outline application should accept the need for details of a development to evolve, within clearly defined parameters, over a number of years;
- The EIA takes account of that evolution need, within those parameters, and reflects the potential effects of such a flexible project in the ES;
- The more detailed the proposal is, the easier it will be to ensure that regulations are complied. The level of detail provided must enable a proper assessment of the likely environmental effects and necessary mitigation measures. When needed a range of possibilities should be considered and a cautious “worst case” approach adopted;

- The "flexibility" referred to is not to be abused: "This does not give developers an excuse to provide inadequate descriptions of their projects. If there is an unnecessary degree of flexibility, and hence uncertainty then consent can be refused" (Planning Inspectorate 2012).

This is of particular interest for renewable energy projects whose nature, where consent is applied for and obtained usually several years before the start of construction works, has the potential to avoid the developer from using any technology or installation improvement that had been considered not viable at the time of assessment (Mainstream Renewable Power 2012). Numerous second offshore wind leasing round (Round 2) adopted this approach to describe their design parameters and had obtained consent (TCE 2012).

According to GWFL (2011) the prime drivers for the need of flexibility could be summarised as giving developers: the ability to optimise projects from a design and economic perspective; the chance to refine the detail design of the project during the procurement phase allowing new technology to be incorporated into the project and; the possibility to maintain a competitive market behaviour in the supply chain.

From what is stated in the PINS Advice Note 9 (Planning Inspectorate 2012) there are some areas of the project that may not be available to be provided with detail at the time of making the request for a scoping opinion. Those that have an impact on the present work are: type and number of WTG and; foundation type. Nevertheless it is also stated that in order to obtain consent for the development some maximum and minimum technical parameters should be stated within the Development Consent Order (DCO) namely: number of WTG; nacelle hub height; blade tip height; clearance above mean sea level (AMSL) and; separation distances between WTG. This meaning that from the scoping stage to the application submission those details have to be stipulated.

Those Rochdale Envelope parameters collated within the reviewed ESs would serve as basis from where the boundaries and limits for the validation of the methodology will be taken (see 4.8).

3.3. Significant Impacts Object of Study

After the review of several ES it was decided to group the different type of impacts according to three categories: physical; biological and; human environment. The main potential impacts will be described according to different subcategory depicting what has been found in the literature review. Potential positive impacts would be presented at the end of this section.

3.3.1. Physical Environment

3.3.1.1. Geology and Water Quality

Geology, sediments and bathymetry should not be changed by the development, so EIA is usually concentrated on potential impacts on the coastline, sandbanks and water quality. Some aspects of the project have a direct impact on the coastline for example the cable landfall. In this case developers suggest that the best method of installation would be directional drilling as it would ensure no long term impacts on the shore. The process consists in installing a duct beneath the intertidal area, in to which the cable will be laid. The alternative would be trenching or laying the cable, with suitable protection, across the intertidal area leading to changes in the hydrodynamics and sediment concentration for a short period of time potentially affecting water quality (Mainstream Renewable Power 2012).

3.3.1.2. Physical Processes

Currents, water levels, waves and sediment transport changes are studied under this section but they have been claimed by the majority of developers as non-sensitive receptors and their focus is generally on how these changes could affect the sediment regime at the coast. In order to do this observations from metocean surveys are used to calibrate and validate regional physical processes model which then are employed to predict changes due to the construction phase of the project and the presence of the WTG and foundations (Mainstream Renewable Power 2012).. No developer have found those changes to be significant.

3.3.1.3. Air Quality

Baseline emissions of NO_x, SO_2 and CO_2 need to be modelled and the predominant wind direction taken into account to estimate the impact the development would cause on the overall air quality of the area. It has been stated that the largest emissions occur during construction while being predicted to be insignificant. As it would encompassed in the section 3.3.4 offshore wind farm developments have a net positive effect on the regional and global air quality. Particularly CO_2 emissions reduction due to energy being generated by a renewable source that would have otherwise been produced from traditional fossil fuel sources. On some circumstances operational WTG have the potential to increase sea fog under certain conditions (Mainstream Renewable Power 2012).

3.3.2. Biological Environment

3.3.2.1. Nature Conservation

Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) are the most important sites for nature conservation as they have been designated under European Legislation. SACs describes sites of importance for species such as marine mammals and migratory fish, as well as habitat features such as reef habitats, while SPAs is used to describe sites of importance for bird species, including seabirds. The SPAs are normally designated for a wide range of seabirds and represent key areas for foraging, breeding and over-wintering for species (Mainstream Renewable Power 2012).

3.3.2.2. Ornithology

The main potential risks for birds are collision; disturbance/displacement; barriers to movement of e.g. migrating birds, or disruption to functional links, for example between feeding and breeding areas; habitat change with associated changes in food availability; and the cumulative effects of these across multiple wind farms (Langston 2010). For guidance purposes in the present work and, extracted from a TCE guidance (Band 2012), the following concepts will be used when referring to:

- **Displacement.** When birds may partially or totally avoid the wind farm development area and therefore are displaced from the underlying habitat.

- **Barrier effects.** When birds may use more circuitous routes to fly between breeding and foraging grounds using more energy to acquire food.
- **Habitat effects.** When birds are attracted or displaced by changes in marine habitats and prey abundance as a consequence of the project.
- **Collision risk.** When birds may be injured or killed by an encounter or collision with WTG or rotor blades.

According to Furness *et al* (2013) displacement is more likely to occur if seabirds avoid the development, whereas collision is more likely to occur when seabirds if they fail.

The magnitude of the disturbance impact could be determined by quantifying the proportion of the regional, national or international populations hosted by the development footprint and a normal 4km buffer zone. In the exact same way the magnitude of the direct and indirect habitat loss could be determined. Barrier effects have been stated as the most complex to quantify and to date all impact assessment have been qualitative (Maclean et al. 2009). In the same report Band collision risk model is suggested to assess the impacts of collisions for all ornithological features.

A quantitative estimate of collision risk for all sea birds species present on the site should be included in the ES for an offshore wind farm development for those species which the level of risk has the potential to be important. The significance of the predicted mortality will depend on the sensitivity of the bird population, the degree of legislative protection and any protected sites in the vicinity which may be designated for that species (Band 2012). Collision risk modelling is usually conducted to determine if there are any significant effects arising from birds colliding with turbines (Mainstream Renewable Power 2012).

3.3.2.3. Marine Mammals

The most common methods to gather information on marine mammals are visual surveys undertaken from boats and acoustic surveys used to detect underwater vocalisations.

The primary potential effect arise from the construction phase and it is associated with pile driving noise. It has the potential to result in lethal effects, physical injury and behavioural effects, either permanently or temporarily, on species of marine mammal present at the area of development. Developers state that behavioural responses are highly variable, both between species and between individuals within a species (Arcus Renewable Energy Consulting Ltd 2012). Marine mammals that are less than 1000m from peak pile driving operations may suffer physical damage (DONG Energy 2006). Effects may range from a mild, short-term avoidance reaction to a long-term displacement, which may then have consequences for the health of animals affected (e.g. if displacement reduces foraging opportunities or affects breeding). Effects were assessed over the short term, in relation to the duration of the piling activity, and over the long-term, in relation to potential population-level affects.

Possible measures to mitigate against potential impacts on marine mammals include foundation type, reduced energy input for piling, soft start-up, use of barriers such as bubble curtains or piling sleeves, use of marine mammal observers, acoustic deterrents and passive acoustic monitoring (Mainstream Renewable Power 2012).

3.3.2.4. Benthic Ecology

A review of published information and site surveys are used to characterise the benthic seabed environment. During the surveys sediment types are examined, dropdown video footage is taken and representative species are sampled in order to be able to classify the benthic environment and habitats in the proposed site according to the established marine habitats classification system developed by the Joint Nature Conservation Committee (JNCC) (Mainstream Renewable Power 2012).

The potential impacts are:

- Habitat loss and disturbance from construction of the wind farm through placement of installation vessels and WTG foundations;
- Increase in SSC and associated turbidity, sediment settlement and scour of benthic communities and potential implications for survival and reproductive success; and
- Electromagnetic fields and heating from operating subsea cables on invertebrates and their different life cycle stages. There is some uncertainty associated with this impact as there is a lack of scientific data on benthic species' responses (Mainstream Renewable Power 2012).

The potential indirect impacts include:

- Changes in hydrodynamics and nutrient transport; and

- Introduction of artificial substrate and alien.

3.3.2.5. Fish and Shellfish Ecology

Site-specific survey and a detailed review of existing literature and data are normally used to obtain information on the species that could be found on the development area. Of special interest are those species that have a commercial importance locally and regionally, or those of conservation importance due to their rarity or sensitivity.

The potential impacts on fish species arise from suspended sediment from construction activities that could reduce visibility acting as a barrier to movement or predation. The sediment deposition could lead to changes to habitats or impacts on fish eggs and larvae. Loss of some habitat is expected to result from the installation of WTG foundations. Besides the fact that many fish species are sensitive to noise makes them susceptible of being affected during the construction phase of the project leading to physical or behavioural changes. Underwater cabling emits an electromagnetic field and some fish species are sensitive to this and could be affected by cabling (Mainstream Renewable Power 2012).

3.3.3. Human Environment

3.3.3.1. Commercial Fisheries

The presence of vessels and machinery during construction could affect fishing vessels operating in the vicinity of the wind farm or cable route making the commercial fisheries one of the most affected sectors by the offshore wind development. However any potential impact will be reduced to the presence of WTG during the lifetime of any project. Impacts to potential fisheries may include the loss or restricted access to fishing grounds; fouling of static gear or changes to towing patterns; and displacement of fishing vessels into other areas. These impacts could be reduced by putting into practice mitigation measures such as sufficient cable burial and the creation of a fisheries working group (Mainstream Renewable Power 2012).

3.3.3.2. Shipping and Navigation

This type of developments may lead to a loss of navigable sea room which may lead to an increase in collision risk impact, both vessel to vessel and vessel to WTG or foundation (Mainstream Renewable Power 2012).

3.3.3.3. Military and Aviation

This section encompasses primary surveillance radars such as: air traffic control radars; military air defence radars; precision approach radars; En-route radars; vessel traffic services radars; and meteorological radars. The presence of WTG causes interference on radar and telecommunications as a result of reflections or by the blockage of signals also known as “shadowing”. This impact is claimed to be mitigated by designating the area over the development as a Transponder Mandatory Zone, where aircraft are required to be equipped with transponders or infill radar to supplement coverage (Mainstream Renewable Power 2012).

3.3.3.4. Maritime Archaeology and Cultural Heritage

Desk based study and archaeological assessment of geophysical and geotechnical survey data are the most common methods used to identify and to establish their current condition of any potential cultural heritage assets that may be affected by the development. Included under this category is everything from recent shipwrecks to vast submerged landscapes. Developers are recommended to characterise any artefacts which are known or have the potential to be in the area due to their hypothetically unique nature. As a mitigation measure exclusion zones are suggested to be maintained around any detected wreck sites (Mainstream Renewable Power 2012).

3.3.3.5. Unexploded Ordnance

Any offshore development taking place into the North Sea are is potentially at risk from ordnance due to military activity occurred during the Second World War. Special care has to be taken when the project area overlaps with current military firing ranges and when any wrecks are detected in the area that could date from the First or Second World War and therefore could contain unexploded ordnance (UXO). To address those issues developers recommend to carry out a risk assessment and full seabed magnetometer scan prior construction (Mainstream Renewable Power 2012).

3.3.3.6. Seascape, Landscape and Visual Impact

Sensitivity of the landscape or the viewer, and the magnitude of change predicted to occur are taken into account in the assessment while staying focused on the long term impact of the development operational phase considered to have a longer impact than the construction stage, this last one deemed to be of short term in comparison. It has to be taken into account that the level of impact experienced by a viewer depends on weather conditions at the time and their sensitivity and viewing opportunity (Mainstream Renewable Power 2012).

As most developer state there is little mitigation applicable to this type of projects to minimise visual impact effects. In this case screening with trees and planting is not possible, and the design of the wind farm has little impact on how it is perceived due to the nature of the marine horizon (Mainstream Renewable Power 2012). One measure could be painting the WTG in a pale grey colour.

3.3.3.7. Socioeconomics, Recreation and Tourism

Normally the socioeconomic benefit is assessed through mathematical models that take into consideration the anticipated project expenditure and available industry data for the installation and operational phases. Some developers suggest that if employment figures are provided in the form of individual jobs the statistics could be misleading. In order to address this issue job years, understood as the representation of the length of the job, should be stated (Mainstream Renewable Power 2012). The majority of the ES reviewed for the present work did not take into account the potential of extending the life time of the project through repowering and therefore socioeconomic figures are for the first 25 years of construction and operation.

Regarding recreational and touristic users there is no agreement when stating if they would be attracted due to the fact of the development being a sustainable technology or pushed away because they consider that WTG spoil the seascape (DONG Energy 2006).

3.3.4. Potential Positive Impacts

Despite the majority of the fore mentioned impacts deriving from negative effects on the environment it is worth mentioning that there are also positive impacts associated with offshore wind development. Taking into account the reduction on Green House

Gasses (GHG) emissions offshore wind generates a long-term positive impact on biodiversity. By 2030 EWEA forecast that 315MT of CO_2 will be offset annually by an offshore wind installed capacity of 150GW (EWEA 2009). Besides several researchers have stated that offshore wind farm developments could benefit the local marine environment in multiple ways (Wilhelmsson et al. 2010). Those considered key from the literature review are described below.

3.3.4.1. Trawling Exclusion and Impacts on Fish

For the context of this work it is important to notice that trawling exclusion does not apply in the UK. However in those countries where fishing within the wind farm boundaries has been banned local fish populations have increased (EWEA 2012). It has been claimed that while fish abundance around WTG foundations has been significantly higher, species diversity has been lower compared against on the seabed (EWEA 2009).

3.3.4.2. Artificial Reef Effects

In the North Sea, oil platforms pipelines and subsea structures were found to attract more fish than previously thought because they were acting as reefs. Researchers from the Aberdeen University defended that if a certain design attracts more fish than another and creates habitats as nursery or spawning grounds, it could potentially be used to modify foundation design (REUTERS 2011).

Boulders used around WTG foundations for the purpose of scour protection could act as artificial reefs, providing good breeding conditions and shelter from currents, and therefore enhancing the biomass of a wide range of organisms (EWEA 2012)(DTU Aqua 2012). Additionally, several researchers have claimed that moorings or foundations may serve as Fish Aggregating Devices for large predatory and pelagic fish (Wilhelmsson et al. 2010). Commercial species could be benefited from this increased concentration of benthos and trawling restrictions leading to more captures available for commercial fisheries due to target species population being augmented (EWEA 2012).

3.3.4.3. Habitat Enhancement

Related to the previous positive impact there is also a chance for offshore wind farm developments to lead to the establishment of new species and new fauna ending up big a new type of habitat with a higher biodiversity (Cox 2011). It could be stated then that projects could have a positive long-term impact on local wildlife and may have, indeed, a little negative effect. Researchers suggested that additional safety zones should be set-up around offshore wind developments to secure and enhance the benefits to the local marine environment (Wilhelmsson et al. 2010). An in countries where trawling fishing is banned inside those types of developments they could be used to protect marine organism and natural habitats if strategically located (Wilhelmsson et al. 2010).

From what has been stated it could be said that offshore wind development could revert the negative impact they have caused to marine users, such as commercial fisheries, by creating fauna refuges that would end up increasing the number of potential captures.

3.3.5. Summary

For the purpose of the present work there will be a special focus on those disturbances related to the WTG and its structure foundation According to what has been mentioned before the key impact related to WTG would be those involving sea birds., marine mammals and benthic fauna, therefore collision risk modelling, construction noise and loss of seabed would be studied. In the present work only direct impacts will be addressed.

Chapter 4. Methodology

4.1. Introduction

A theoretical location, with specific parameters such as wind velocity, water depth and distance to shore, will be used to assess the different WTG and foundations combinations. This theoretical location will try to reflect the different options that could be found in TCE Round 2 developments. Wind resource data will be used to evaluate the different WTGs performance, mainly their power output. The different foundations associated impacts will be assessed according to the importance present in the documentation submitted to the Planning Inspectorate by the developers (ES, NTS and any other source of significance).

Finally a matrix with weighted criteria will be developed to determine the best solution for the particular theoretical location.

In every step of the process and with the intention to avoid repetition of the different WTG and foundation names a labelling system will be used. This meaning that every combination will be refer to as WTGxxFxx where WTGxx will be one of the 14 options and Fxx one of the 8 options foundations object of study. For example WTG01F01 will stand for a 20MW WTG and a steel monopile substructure. The complete list of combinations could be seen below:

Table 4 Combination Label Equivalence

	Manufacturer	Model	Nameplate (MW)
WTG01	Upwind	20MW	20
WTG02	Sway	10 MW	10
WTG03	Aerodyn	8.0 MW-168	8
WTG04	Samsung	7.0-171	7
WTG05	Senvion	6.2M152	6.15
WTG06	Siemens	SWT-6.0-154	6
WTG07	Hyundai	HQ5500/140	5.5
WTG08	XEMC-Darwind	XE/DD126	5
WTG09	Bard	VM	5
WTG10	GE Energy	4.1-113	4.1
WTG11	Siemens	SWT-3.6-120	3.6
WTG12	Siemens	SWT-3.0-108	3
WTG13	Nordex	N90/2500	2.5
WTG14	Gamesa	G87/2000	2

	Foundation Type
F01	Steel Monopile
F02	Concrete Reinforced Monopile
F03	Tripod
F04	Jacket Piled
F05	Jacket Suction
F06	Gravity Base
F07	IBGS
F08	Suction Bucket

4.1.1. Summary WTG Inputs for the Analysis

Not every parameter was available for all the different WTG and therefore logarithmic and linear regression were performed to extrapolate the missing data. Note that those parameters that are shown in *italic* and starred (†) have been extrapolated (see Table 5). Graphs showing the regressions carried out could be seen in Appendix II.

Table 5 WTG Parameters

Manufacturer	Model	Power (kW)	d (m)	Hub height (m)	Cut-in (m/s)	Rated speed (m/s)	Cut-out (m/s)	Nominal speed (rpm)
Upwind	20MW	20	252	152	3	10	25	6.05
Sway	10 MW	10	164	110	4	13	28	12
Aerodyn	8.0 MW-168	8	168	100	3.5	12.5	25	11.5
Samsung	7.0-171	7	171	110	3	11.5	25	*11.9* †
Senvion	6.2M152	6.15	152	110	3.5	11.5	30	10.1
Siemens	SWT-6.0-154	6	154	110	4	13	25	11
Hyundai	HQ5500/140	5.5	140	100	3.5	12	25	*13.2* †
XEMC-Darwind	XE/DD126	5	126	100	3	11.5	25	*13.7* †
Bard	VM	5	122	90	3	12.5	25	*13.7* †
GE Energy	4.1-113	4.1	113	85	3.5	14	25	19
Siemens	SWT-3.6-120	3.6	120	85	4	12.5	25	13
Siemens	SWT-3.0-108	3	108	79.5	4	11.5	25	16
Nordex	N90/2500	2.5	90	70	3	13	25	18.1
Gamesa	G87/2000	2	87	67	4	15	25	19

Manufacturer	Model	Swept area (m2)	Power density (m2/kW)	Blades	Blade length	Max Chord (m)	Power Coefficient	First Installation
Upwind	20MW	49875.92	2493.8	3	123	9.3	0.59	Theoretical
Sway	10 MW	21124.07	2112.41	3	67	*6.00* †	0.35	2015
Aerodyn	8.0 MW-168	22167.08	2770.88	2	*81.25* †	*6.14* †	0.3	No Data
Samsung	7.0-171	22965.83	3280.83	3	83.5	*6.25* †	0.33	2013
Senvion	6.2M152	18145.84	2950.54	3	*73.50* †	4.5	0.36	Q4 2014
Siemens	SWT-6.0-154	18626.5	3104.42	3	*74.47* †	*5.65* †	0.24	2014
Hyundai	HQ5500/140	15393.8	2798.87	3	*67.68* †	*5.15* †	0.34	2014
XEMC-Darwind	XE/DD126	12468.98	2493.8	3	*60.89* †	*4.66* †	0.43	No Data
Bard	VM	11689.87	2337.97	3	*58.95* †	5.96	0.36	2010
GE Energy	4.1-113	10028.75	2446.04	3	*54.59* †	*4.20* †	0.24	2011
Siemens	SWT-3.6-120	11309.73	3141.59	3	58.5	*4.45* †	0.27	2009
Siemens	SWT-3.0-108	9160.88	3053.63	3	53	3.4	0.35	2009
Nordex	N90/2500	6361.73	2544.69	3	*43.44* †	*3.39* †	0.29	2006
Gamesa	G87/2000	5944.68	2972.34	3	42.5	3.36	0.16	2004

4.2. Wind Data

The main purpose of this part of the work was to assess the differences between using wind data gathered from deployed instrumentation and the one that could be extrapolated from any weather dataset that is available online. Data from to different met mast locations will be analysed to estimate the differences between an electricity production forecast when using different time step resolutions namely: 10 minute, hourly, daily, and monthly as well as using a Weibull distribution pdf.

Reanalysis data for a 20 year period would be used to describe the expected energy production of the theoretical wind farm location. Despite the data being freely available online it has to be collected and processed before it could be analysed. This Reanalysis data coming from to different sources will be compared against data acquired from a meteorological mast available in the Marine Exchange website. The one that showed the best coefficient of determination (R^2) with the real data will be used for the techno economic analysis to obtain the energy output for the lifetime of the project. During this analysis parameters for the WGT11 (Siemens SWT-3.6) will be used as it has been the most commissioned model to present.

It has to be taken into account that for the electricity generation analysis wind speed will be extrapolated to each WTG hub height (see Table 5).

4.3. Collision Risk

Seabirds impacts derived from the development of a new wind farm project constitute a major barrier to the UK offshore wind development as it has been already discussed (see section 3.3). The main impacts associated with those developments are that they could lead to potential risks of collision, disturbance and even constitute a barrier to seabird movement such as migratory colonies.

In order to estimate the collision risk for a determinate specie there is a collision risk model (CRM) developed by Band, as part of the Strategic Ornithological Support Services programme, project SOSS-02 (Band 2012). A spreadsheet is freely available to standardise the calculations and result reporting. This spreadsheet will be used for this part of the analysis. According to the same guidance report the minimum information needed to estimate collision mortality has to proportionate:

- Information derived from bird survey such as number of birds flying through or around the site as well as their flight height.
- Bird change of behaviour, either avoidance or attraction by the development.
- WTG physical details such as number, size and rotation speed of the blades.
- Bird physical details such as size and flight speed.

The CRM has been adapted to the offshore environment and it is constituted by 6 stages:

A. Assemble data on the number of flights potentially at risk from WTG.
B. Estimate the potential number of bird transits through rotors of the wind farm with the flight activity data.
C. Calculate the probability of collision during a single bird rotor transit.
D. Multiply probability by the potential number to obtain the potential collision mortality rate taking into account the time that WTG are not operational and no avoidance from birds.
E. Use of the proportion of birds likely to avoid or be attracted by the WTG.
F. Express the uncertainty surrounding such a collision risk estimate.

The model was been extended in 2012 version to make use of available and robust flight height distribution data; and to include a methodology to address migrating birds, for which survey data on flight activity may be limited (Band 2012).

There are a series of assumptions and limitations associated to this model from Band (2012):

- The fact that the risk is WTG based and does not take into account layout and spacing between them as it considers that each WTG operates within its own airspace.
- Density of flying birds per unit horizontal area of the development and the proportion flying at WTG height are the core measures of flight activity.
- Birds approaching a WTG in an oblique angle has been simplified to a perpendicular approach that could lead to a 10% underestimation of collision risk for large birds (does not affect the present work).
- Flight height distribution is only taken into account in the extended model. The basic model considers the risks only to birds flying above the minimum and below the maximum height of the rotors assuming a uniform distribution of

flights. This is not accurate as most of seabirds fly at relatively low heights over the sea surface.

- Worst case usage is not recommended because they could lead to an overly pessimistic result.
- Collision risk for an entire development could assessed through spatial exploration of risk.
- It could be used for onshore wind farms.

It is worth mentioning that there are two types of avoidance behaviour that different species have at offshore wind farms namely: "macro-avoidance" and "micro-avoidance". Macro-avoidance occurs if birds alter their flight path to keep clear of the whole project, while micro-avoidance occurs when birds enter the project but take evasive action to avoid individual WTG (Furness et al. 2013). Data on those avoidance rates is very limited and inconsistent (Cook et al. 2012). Besides collision avoidance rates are complicate to estimate as there is not enough post-construction monitoring or in case of existing those values are not disclosed and therefore could not be evaluated by experts.

Even though current WTG are capable of regulating their output by changing their pith from the ES analysed it has been observed that the normal value used for WTG pith was 10º while 25 to 30º are suggested by the guidance described in this section (Band 2012). A sensitivity analysis will be provided and the ES value would be used for the Section 0 calculations.

4.4. Noise Impact

As explained in the Chapter 3 (see section 3.3), noise impact during construction is a huge issue when evaluating the appropriateness of an offshore wind farm development. Underwater noise could be described as a pressure wave that travels through the water which can travel large distances in the ocean compared to sound in air, due to relatively low acoustic absorption (EAOWL 2012). The amplitude of the sound is normally described in terms of the sound pressure in Pascal (Pa). Nevertheless it is normally expressed in decibels (dB) relative to a reference pressure which is 1µPa for underwater sound by convention. For the present work the received level of sound pulse is the zero peak sound pressure level (peak SPL) in dB re 1µPa will be used to describe it (EAOWL 2012).

As many species of marine mammal use sound for prey detection, communication and navigation there is a risk of anthropogenic noise exceeding natural background levels and falling within the audible range of a marine mammal to potentially cause disturbance or even in extreme cases severe injuries (GWFL 2011a).

The potential harmful effects of high-level underwater noise for marine mammals are dependent on the source noise (frequency and dB), species, distance from source and factors such as noise attenuation. They could be categorised into (Parwin et al. 2006):

- **Lethal:** at very close range from the source the peak pressure levels have the potential to cause death, or severe injury leading to death;
- **Physical injury:** at greater range the construction noise may cause physical injury to organs surrounding gas containing structures of the body;
- **Hearing impairment:** at high enough sound levels, generally taken to be 180 dB re 1µPa for all species of marine mammals, the underwater sound has the potential to cause permanent hearing impairment in marine species (Nehls et al. 2007) and;
- **Behavioural response:** Behavioural changes that could lead to marked variation in responses across studies (GWFL 2011a).

For the purpose of the present analysis the hearing impairment effect would be assessed and for any value obtained over the 180 dB re 1µPa limit it would be considered that mitigation measures would be required and therefore installation cost for that type of foundation are expected to be higher.

Values for different peak SPL in dB re 1µPa will be presented from data gathered from UK Wind farms developments and processed to obtain an equation that will be used to estimate the peak SPL level for the different foundation options.

For the present study a 90 dB noise peak level would be considered for those foundations that are not piled into the seabed. This value would be related to the noise associated with the installation vessel (Shearer 2013).

4.5. Seabed Loss

Most of the North Sea seabed consists of sandy soil that is constantly moving due to waves and current. Those current and wave motions are increased locally when a structure is placed offshore. A hole is created around the structure due to the fast flowing water stirring sand particles transporting them away from the structure (Tempel et al. 2005). This is what is known as scour. Therefore in addition to the foundation measures to reduce or eliminate scour, also known as scour protection, will be necessary. For the present work it has been considered that all WTG foundations would require scour protection. According to Arcus Renewable Energy Consulting Ltd. (2012) scour protection could be:

- **Static.** When a layer of fine grade rock or gravel is placed on the seabed prior to the installation of the foundation. An armour layer comprising rock boulders is then installed once the structure is in place and;
- **Dynamic**. The WTG foundation is installed after scour protection has been installed at each location.

For the purpose of the present analysis data from different ES has been gathered and processed to be able to extrapolate the values for the different types of WTG substructures object of study. Foundation footprint and scour protection will be analysed separately to evaluate the best and worst options. Finally values for each type of foundation will be added together to describe the habitat or seabed loss. It will not be taken into account that scour protection could lead to positive impacts as it has been explained in section 3.3.4 due to the lack of available figures to estimate that impact.

4.6. Costs Analysis

Cost figures for different WTG and substructures are considered by developers as sensitive information. Due to this it was not possible to find values that allowed an accurate analysis of the different combinations.

The "Levelized Cost of Electricity (LCoE)" approach was estimated to be the most suitable option as it would provide the analysis with a maximum price for the different structures. An standard formulation to calculate the LCoE was obtained from the literature review (Heptonstall et al. 2012) at can be seen below:

Equation 2 Levelized Cost of Energy

$$LCoE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where

- $LCoE$ = Average lifetime levelized electricity generation cost
- I_t = Investment expenditures in the year *t*
- M_t= Operations and maintenance expenditures in the year *t*
- F_t = Fuel costs in the year *t*
- E_t = Electricity generation in the year *t*
- r = Discount rate
- n = Life of the system

The following assumptions will be used. Fuel costs per year are not considered in the present work, operations and maintenance expenditures are assumed to be a fix value that has to be discounted and that all the investment is taken into account in the first year of operation.

From the literature review the following figures were obtained:

- A target LCoE of 156 £/MWh that corresponds to an average of 4 different sources (The Crown Estate 2012; Ernst & Young 2009; Mott MacDonald 2011; ARUP 2011).
- An average of 118.33 £k/MW p.a. for the of operation and maintenance costs.
- A WTG and foundaiton CAPEX ranging from 35 to 50% and between 20 to 25% of the total capital expentire respectively (Greenacre 2013).
- An estimated wake losses percentage of 12.4 extracted from the Horns Rev. offshore wind farm (Sørensen et al. 2006).
- HVAC transmission associated cable losses of 2% for an offshore wind farm located 20km from shore (Ackermann et al. 2005).

With this target LCoE the Equation 2 Levelized Cost of Energy could be solved to obtain I_1 as it can be seen below.

Equation 3 LCoE first year investment

$$I_1 = \left\{\left[\left(LCoE \times \sum_{t=1}^{n} \frac{E_t}{(1+r)^t}\right) - \sum_{t=2}^{n} \frac{M_t}{(1+r)^t}\right] \times (1+r)\right\} - M_1$$

Once I_1 is obtained minimum and maximum capital cost values for WTG and foundations could be obtained. Due to this LCoE being highly affected by the annual generated electricity cost per foundation will have to be analysed according to qualitative criteria such as stage of development or employed materials. In this part of the analysis a comparison against a LCoE target of 100 £/MWh will be provided to try to understand the implications that that could have for the offshore wind energy in the future.

4.7. Solution Analysis

The different values obtained from the subsection analysis will be used to populate a matrix according to the labelling previously explained (see Table 4). It has to be taken into account that for the "Seabed loss" variable the value obtained was per foundation and therefore it has to be multiplied by the number of WTG for each combination.

Table 6 Combination Analysis Summary

	WTG				Foundations	
	Energy Production (GWh)	CRM				
		Herring	Red-throated Diver	Razorbill	Installation Noise	Seabed loss
WTGxxFxx						

Data obtained from the previous steps would correspond to different variables and therefore could not be compared nor added together. In order to address this issue the following a three stage process will be used.

In the first stage the worst option for each criteria would be used to transform every value into a percentage of improvement from that worst option. This will provide an estimation of how better this analysed option is in comparison with poorer performer. It has to be taken into account that depending on the variable object of study the worst performer could imply the bigger or the lower value. This would allow to add variables that were before of different magnitudes to obtain an overall value for the combination.

During the second stage those percentages of improvement will be transformed into an actual performance rating that will be derived from 10 intervals. In the third and last stage weighting factors would be applied to the previous performance values and the resultant values will be added together to obtain the final weighted value. Being those factors highly subjective different scenarios and a sensitivity analysis will be provided to understand their impact.

Lastly those values obtained from the fore mentioned process will be transformed with the foundations suitability equations (see section 2.5.2). Applying in this manner a sort of correction as it takes into account more parameters than those addressed in the previous steps of the methodology, such as soil conditions, stage of development and, construction costs.

A worked example would be provided for one type of WTG with the rest of the options being following the same procedure. Tables summarising the process results could be seen in Appendix III.

4.8. Validation and Verification

As part of the sixth chapter data from a commissioned project will be used to test the aforementioned process and try to extrapolate the likelihood scenario that could happen in the next TCE Round 3 projects. Due to the Round 2 project have been already commissioned data from their ES would be used to select the combinations that are going to be evaluated and compared against the final installed option. It is expected that some of the WTG do not comply with the limitations set by the Development Consent Order granted to the project and therefore should be ruled out of the verification process.

Chapter 5. Different Combinations Results and Analysis

5.1. Location Definition

In order to be able to validate the forthcoming process the theoretical location parameters will be based on some Round 2 real projects. For those analysis that needed a more specific context data from the Galloper project was used. This was due to it being the closest one to the available wind data that had public information available. The main input used during this chapter are presented below.

- Installed Capacity: 404MW (Round 2 average see Table 1)
- Extension 174 km2 (Galloper project)
- Width WE 25 km NS 7 km (Galloper project)

The main sea bird species and population figures for them will be presented in the section 4.3. In the same way any specific data required for any section will be provided in it.

5.2. Wind Resource Analysis

In this subsection different wind data sources will be assessed to decide which will be the best to be used to calculate our theoretical wind farm production.

5.2.1. Collected Wind Data

Two types of wind dataset were used. Monitoring data from actual meteorological stations and Reanalysis data from different weather models.

Real data from the Gunfleet Sands II meteorological mast was available for the period between February 2002 and August 2005 at the Marine Exchange Website. The other source was from the FINO 2 research platform from the Baltic Sea.

Regarding the Reanalysis wind data a freely available dataset was accessible at the "Goddard Earth Sciences Data and information Services Center" as part of the Modern Era Retrospective-Analysis for Research Applications (MERRA) Data Subset. This data subset has the advantage that an area of interest could be selected to narrow the data to a particular latitude and longitude area. However it presented the drawback that the dataset was provided in individual daily files. The second one was obtained after a personal communication and its origin will not be disclosed.

The main sources of wind data and their characteristics are summarized below.

Table 7 Wind Data Datasets Characteristics

Dataset	Period	*Zref* (m)	Time step	Method
Gunfleet Sands II	Feb 2002 - Aug 2005	60	10-min	Met Mast
FINO 2	May 2008 - Apr 2011	100	10-min	Met Mast
MERRA MDISC	Jan 1981 - Dec 2013	10	Hourly	Reanalysis
Confidential Source	Jan 1992 - Dec 2013	100	Hourly	Reanalysis

Notice that *Zref* stands for the measurement height as it was explained in Equation 1 Wind power law.

5.2.2. Wind Data Analysis

Data provided from the Gunfleet Sands II meteorological station was processed to describe the wind resource available at our theoretical location. In this section a wind rose and a "bins" categorisation are provided. As expected the main wind direction is SW and the highest wind speed occurrence are for the range between 8 and 12m/s.

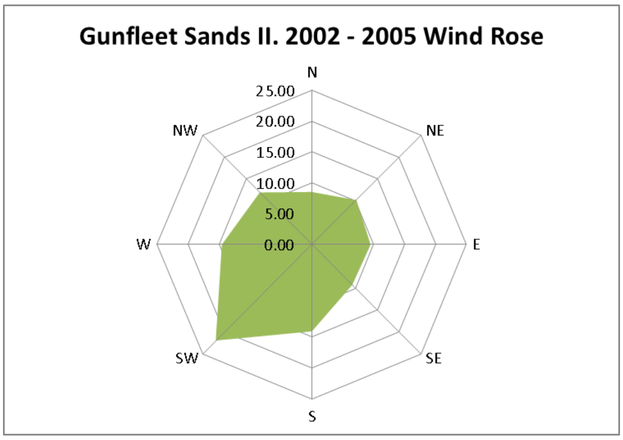


Figure 7 Gunfleet Sands II. 2002 - 2005 Wind Rose

Table 8 Gunfleet Sands II. 2002 - 2005 Wspd Frequency and Direction

Wspd	N	NE	E	SE	S	SW	W	NW
<4	1.49	1.31	1.70	2.30	2.10	1.88	1.83	1.65
<8	4.09	3.91	3.78	4.82	4.94	5.20	5.55	5.47
<12	2.61	3.24	2.75	1.77	4.44	8.34	4.57	3.81
<16	0.31	1.53	1.16	0.33	2.04	5.15	2.04	0.89
<20	0.03	0.19	0.11	0.02	0.49	1.20	0.48	0.11
<24	0.00	0.01	0.00	0.00	0.06	0.19	0.07	0.01
>24	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00

5.2.3. Wind Resource Estimation

When analysing the different wind turbine options it has been taken into account the difference between the hub height and the height at which data from Gunfleet Sands II met mast was registered. The power law (section 2.3.2) was used and the wind speed varied less than 5%.

In order to calculate the turbine power from wind speed the WTGs are considered idealized machines. According to Manwell et al. (2010) the formulae is as follows:

Equation 4 Power from wind speed

$$P_{WTG} = 0.5 \times Cp \times \rho \times A \times U^3$$

Notice that each WTG capacity factor was obtained from their rated output and can be seen in Table 5.

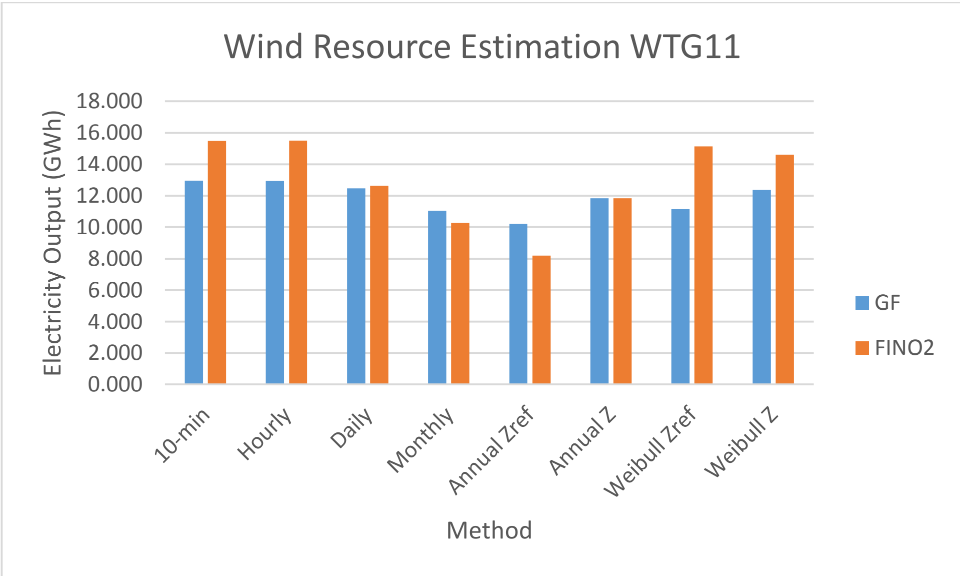


Figure 8 Electricity Generated Comparison

The above graphic shows clearly that annual and monthly data should not be used to estimate wind power output as their results are far from those obtained with the most accurate meteorological mast data.

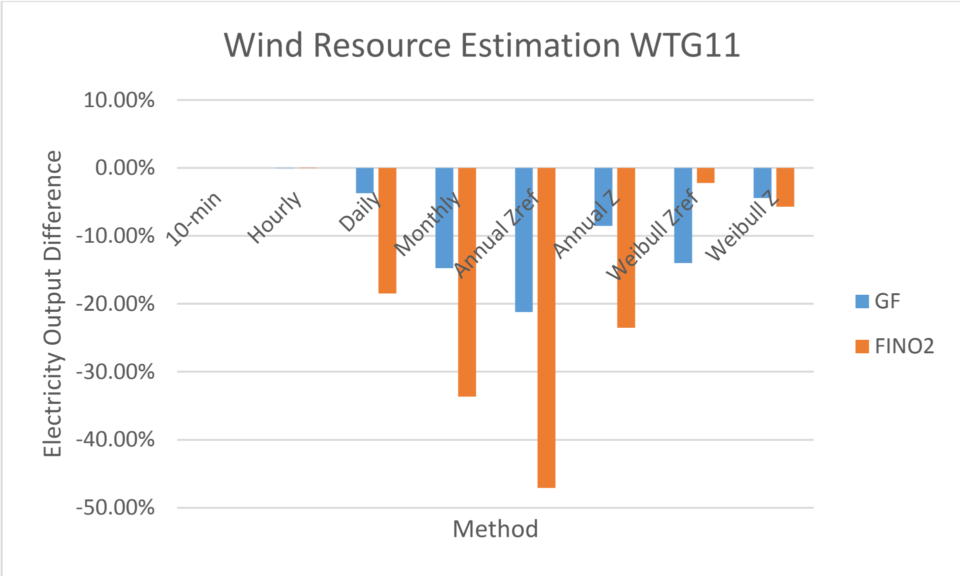


Figure 9 Electricity Output Difference

As we can see from the previous figure the hourly data provides a very accurate prediction of the electricity generated being around a 0.06% difference against the one obtained from the 10 minute data.

Table 9 Wind Resource Estimation Method Comparison

WTG11	10-min	Hourly	Daily	Monthly	Annual *Zref*	Annual *Z*	Weibull *Zref*	Weibull Z
GWh	12.95	12.94	12.47	11.04	10.20	11.85	11.14	12.37
Capacity Factor	41.06%	41.04%	39.54%	35.00%	32.35%	37.56%	35.32%	39.24%
DownTime	11.22%	10.56%	4.11%				12.07%	10.85%

When using Weibull distribution pdf it is worth mentioning that, for the Gunfleet Sands II dataset, wind data need to be extrapolated to the required WTG hub height to obtain the best results as it can be seen in the previous table and *Figure 9*.

Due to the theoretical wind farm being expected to generate electricity for a 20 year period long-term wind data is required. Reanalysis data from different sources was assessed in order to select the most appropriate. Wind data with hourly resolution was selected due to its proven accuracy. MDISC and a confidential source were against the meteorological mast one in order to determine the best correlation.

Table 10 2003 Reanalysis Data Correlation

Variable	Observations	Minimum	Maximum	Mean	Std. deviation	Pearson	R^2
GF_2003	8760	0.000	22.538	8.783	3.770	1.000	1.000
CONF_2003	8760	0.100	23.090	9.013	3.989	**0.881**	**0.777**
MDISC_2003	8760	0.000	23.175	8.579	4.074	0.866	0.750

Table 11 2004 Reanalysis Data Correlation

Variable	Observations	Minimum	Maximum	Mean	Std. deviation	Pearson	R²
GF_2004	8784	0.000	24.510	8.417	4.645	1.000	1.000
CONF_2004	8784	0.000	26.310	9.331	4.482	**0.836**	**0.698**
MDISC_2004	8784	0.000	28.097	9.703	4.919	0.830	0.689

As it can be seen from the data summarised into Table 10 and Table 11 the reanalysis data that provides a best fit with the meteorological data is the one correspondent with the CONF dataset (highlighted in bold). Therefore this dataset will be used for the rest of the analysis to determine the electricity output of our theoretical wind farm.

An example of 2004 Weibull distribution reduced versions of the 3 datasets is provided below with an interval resolution of 0.5 m/s wind speed difference. From a simple visual comparison it can be stated that the wind speed distribution is stretched towards the highest values between 15 and 20 m/s. Besides it has been noticed that in the MERRA dataset there is no value with a density over 0.1 while in the other two datasets there are at least three intervals over that value.

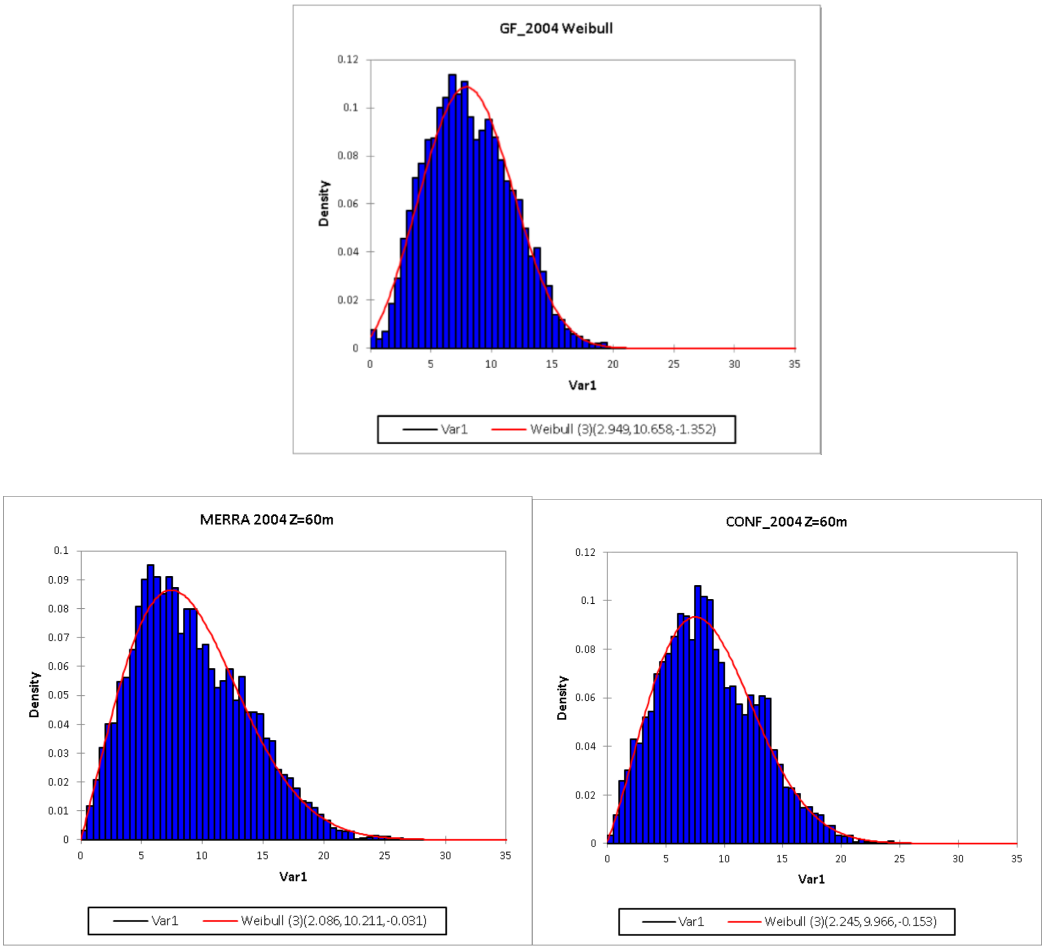


Figure 10 2004 Weibull Distribution Comparison

As the Confidential Data set has proven to be the most accurate and reliable option for the analysis the total life time generation could be calculated for each of the WTG options. From the graph that is provided in the following page (see XXX) it could be stated that as expected the WTG01, of 20MW capacity, is the one that has the best GWh/MW ratio mainly due to its power coefficient being exactly the same as the Betz limit. It is followed closely by WTG04, 05 and 08 all three options sharing a low rated speed of 11.5m/s that has probably allowed them to start capturing at their maximum earlier than other options. The worst option was the WTG14 that a GWh/MW ratio close to half of the 6 best options (highlighted in green in the table).

This total life time generation would prove its importance during the rest of the process mainly for the LCoE analysis.

Table 12 WTG Combinations Total Life Time Generation

	Total GWh	Capacity	GWh/MW	Yr01	Yr02	Yr03	Yr04	Yr05	Yr06	Yr07	Yr08	Yr09	Yr10
WTG01	2160.88	20	108.04	110.07	107.58	109.84	110.84	105.86	104.78	117.72	110.57	109.96	108.73
WTG02	831.77	10	83.18	43.11	40.74	42.51	42.74	40.71	39.33	46.40	44.32	43.73	41.33
WTG03	696.03	8	87.00	36.04	34.08	35.57	35.81	34.11	32.97	38.71	36.96	36.49	34.76
WTG04	695.16	7	99.31	35.75	34.26	35.48	35.72	34.14	33.15	38.41	36.50	36.12	34.96
WTG05	611.13	6.15	99.37	31.39	30.19	31.19	31.39	29.98	29.13	33.80	32.08	31.81	30.69
WTG06	498.29	6	83.05	25.87	24.33	25.47	25.62	24.42	23.57	27.77	26.55	26.18	24.80
WTG07	508.26	5.5	92.41	26.23	24.97	25.97	26.13	24.94	24.14	28.18	26.87	26.55	25.49
WTG08	489.99	5	98.00	25.21	24.14	25.02	25.19	24.06	23.35	27.09	25.76	25.49	24.63
WTG09	427.65	5	85.53	22.15	20.93	21.86	22.00	20.96	20.25	23.81	22.73	22.44	21.32
WTG10	284.84	4.1	69.47	14.81	13.88	14.61	14.59	13.97	13.47	16.01	15.26	15.12	13.91
WTG11	304.25	3.6	84.51	15.77	14.88	15.55	15.65	14.91	14.39	16.96	16.19	15.97	15.16
WTG12	283.64	3	94.55	14.62	13.96	14.48	14.58	13.92	13.48	15.73	14.96	14.80	14.24
WTG13	191.47	2.5	76.59	9.95	9.34	9.79	9.83	9.38	9.05	10.71	10.24	10.11	9.44
WTG14	114.21	2	57.11	5.93	5.57	5.91	5.82	5.60	5.41	6.47	6.13	6.13	5.48

	Yr11	Yr12	Yr13	Yr14	Yr15	Yr16	Yr17	Yr18	Yr19	Yr20
WTG01	107.75	102.39	101.91	107.51	107.43	107.49	112.36	104.12	101.84	112.11
WTG02	41.31	37.85	39.37	40.68	41.58	42.73	44.20	39.37	36.62	43.15
WTG03	34.57	31.85	32.80	34.11	34.74	35.55	36.81	33.02	30.92	36.15
WTG04	34.57	32.25	32.51	34.28	34.59	35.10	36.49	33.19	31.60	36.07
WTG05	30.38	28.29	28.58	30.12	30.42	30.92	32.15	29.17	27.76	31.70
WTG06	24.77	22.71	23.58	24.38	24.90	25.54	26.43	23.59	21.95	25.87
WTG07	25.26	23.40	23.85	24.97	25.33	25.82	26.78	24.17	22.82	26.40
WTG08	24.36	22.70	22.93	24.15	24.39	24.77	25.74	23.38	22.22	25.42
WTG09	21.24	19.54	20.18	20.95	21.35	21.87	22.65	20.28	18.94	22.19
WTG10	14.20	12.75	13.68	13.89	14.33	14.71	15.31	13.45	12.18	14.70
WTG11	15.12	13.88	14.37	14.90	15.20	15.58	16.13	14.41	13.44	15.80
WTG12	14.10	13.08	13.29	13.95	14.13	14.38	14.94	13.50	12.77	14.73
WTG13	9.52	8.66	9.14	9.35	9.60	9.87	10.22	9.05	8.31	9.90
WTG14	5.72	4.98	5.52	5.54	5.78	5.93	6.26	5.38	4.78	5.87

Table 13 WTG First Year of Operation Availability

	Jan	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic
WTG01	90.9%	92.2%	97.2%	91.8%	95.6%	90.7%	93.1%	95.8%	97.2%	97.6%	97.9%	95.7%
WTG02	86.7%	87.5%	95.3%	86.7%	92.9%	82.9%	89.2%	92.5%	92.6%	95.2%	96.1%	92.5%
WTG03	88.6%	89.7%	96.0%	88.6%	93.7%	85.8%	91.8%	94.0%	95.1%	96.9%	96.9%	94.0%
WTG04	90.3%	91.8%	97.0%	91.0%	95.3%	90.4%	92.9%	95.4%	97.2%	97.6%	97.6%	95.6%
WTG05	88.6%	89.7%	96.0%	88.6%	93.7%	85.8%	91.8%	94.0%	95.1%	96.9%	96.9%	94.0%
WTG06	86.7%	87.5%	95.3%	86.7%	92.9%	82.9%	89.2%	92.5%	92.6%	95.2%	96.1%	92.5%
WTG07	88.6%	89.7%	96.0%	88.6%	93.7%	85.8%	91.8%	94.0%	95.1%	96.9%	96.9%	94.0%
WTG08	90.2%	91.7%	97.0%	90.8%	95.3%	90.4%	92.9%	95.4%	97.2%	97.6%	97.6%	95.6%
WTG09	90.2%	91.7%	97.0%	90.7%	95.3%	90.4%	92.7%	95.3%	97.1%	97.6%	97.6%	95.3%
WTG10	88.2%	89.4%	96.0%	88.2%	93.7%	85.0%	91.4%	93.8%	95.0%	96.6%	96.8%	93.4%
WTG11	86.3%	86.9%	94.6%	85.8%	92.5%	80.7%	88.3%	91.9%	91.9%	94.1%	96.1%	92.3%
WTG12	86.0%	86.8%	94.6%	85.7%	92.2%	80.6%	87.6%	91.9%	91.9%	94.1%	96.0%	92.3%
WTG13	90.1%	90.9%	96.5%	90.4%	94.8%	88.9%	92.5%	95.2%	96.8%	97.3%	97.5%	95.3%
WTG14	85.8%	86.6%	94.5%	85.1%	92.1%	80.0%	86.8%	91.4%	91.5%	93.5%	95.8%	91.9%

5.3. Collision Risk Modelling

From the literature review and according to Furness *et al.* (2013) three species have been selected with the population values being taken from GWFL (2011). From the Furness *et al.* (2013) paper it has to be taken into account that they provide a collision risk ranked list of species considering: percentage of birds flying at blade height, flight agility, percentage of time flying, nocturnal flight and, conservation importance and; for the disturbance from habitat another ranked list considering: disturbance by ship and helicopter traffic, habitat use flexibility and, conservation importance.

Table 14 Bird Species for the Analysis (Furness et al. 2013; GWFL 2011b)

Species	Collision Risk	Disturbance	Total Flyway Population
Herring gull	High	Low	1,400,000
Red-throated diver	Moderate	High	75,000
Razorbill	Low	Moderate	482,000

For the same bird species the parameters that were used in the CRM sourced from an ornithology technical report (Collier et al. 2013) are shown in the table below.

Table 15 Bird Species Parameters used in CRM (Collier et al. 2013)

Species	Length (m)	Wingspan (m)	Flight speed (m/s)	Flapping (0) or gliding (1)	Nocturnal activity factor (1-5)	Proportion at rotor height
Herring gull	0.61	1.44	12.8	0	3	0.321
Red-throated diver	0.74	1.1	18.6	0	1	0.02
Razorbill	0.38	0.655	16	0	1	0.000

Figures for WTG operating monthly percentages from the previous section (see Table 13) are used to calculate the potential collision mortality risk using the below monthly population from GWFL (2011).

Table 16 Bird Species Monthly Population for CRM (GWFL 2011b)

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Herring gull	0.172	0.184	0.029	0.029	0.144	0.057	0.017	0.017	0	0.132	0.040	1.506
Red-throated diver	0.023	0.069	0.466	0	0	0	0	0	0	0	0	0
Razorbill	1.247	1.408	0.822	0.615	0.172	0	0	0	0.029	0.305	0.954	0.402

As every spreadsheet calculation follows the same procedure but with different WTG parameters (see Table 5) only an example of the calculations for the theoretical "worst case" WTG14 could be seen in Appendix IV and Appendix V.

A sensitivity analysis could be seen in Figure 11 below will be performed to the WTG pitch parameter as there were some discrepancies between what is common practice between developers and what suggested by Band (Band 2012). It could be seen from the analysis that the Herring gull CRM expected values could increase up to 25% if 30º pitch angle is selected. Nevertheless the value observed in the ES during the literature review will be used for this analysis.

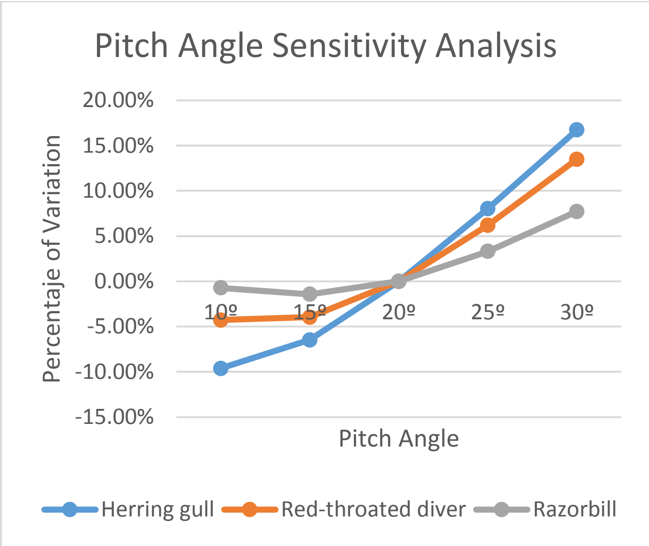


Figure 11 CRM Pitch Angle Sensitivity Analysis

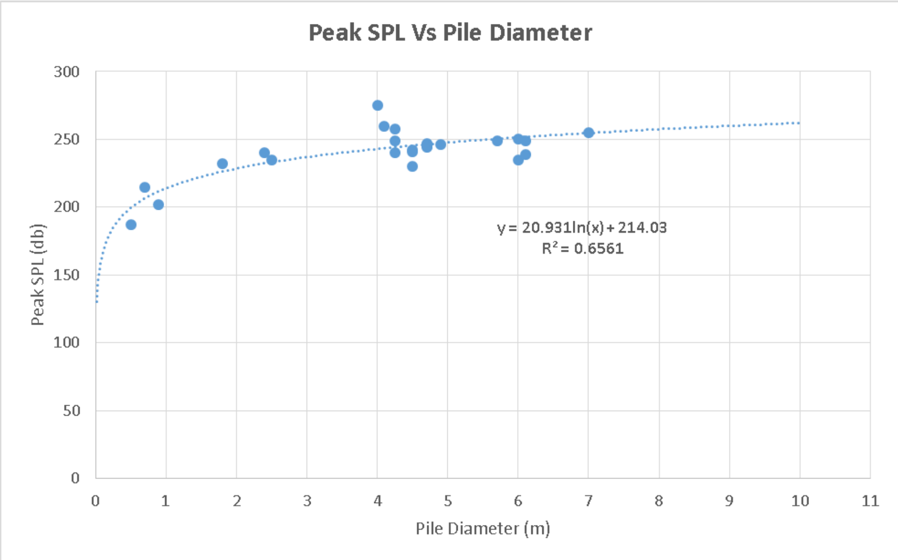
After performing the CRM analysis for the three species and the 14 different types of WTG from the results obtained (see Table 17) it could be stated that WTG01 is the best option regarding collision risk impact and that as it could be expected WTG14 is the worst performer.

Table 17 CRM Final Results with and without Avoidance Rates

No avoidance	**Herring gull**	**Red-throated diver**	**Razorbill**	*98% avoidance*	**Herring gull**	**Red-throated diver**	**Razorbill**
WTG01	0.25%	0.08%	0.09%		0.00%	0.00%	0.00%
WTG02	0.34%	0.11%	0.12%		0.01%	0.00%	0.00%
WTG03	0.30%	0.10%	0.10%		0.01%	0.00%	0.00%
WTG04	0.59%	0.17%	0.18%		0.01%	0.00%	0.00%
WTG05	0.45%	0.15%	0.15%		0.01%	0.00%	0.00%
WTG06	0.54%	0.18%	0.19%		0.01%	0.00%	0.00%
WTG07	0.57%	0.19%	0.20%		0.01%	0.00%	0.00%
WTG08	0.59%	0.20%	0.20%		0.01%	0.00%	0.00%
WTG09	0.70%	0.23%	0.24%		0.01%	0.00%	0.00%
WTG10	0.70%	0.24%	0.24%		0.01%	0.00%	0.00%
WTG11	0.76%	0.25%	0.26%		0.02%	0.01%	0.01%
WTG12	0.79%	0.27%	0.26%		0.02%	0.01%	0.01%
WTG13	0.95%	0.32%	0.32%		0.02%	0.01%	0.01%
WTG14	1.15%	0.39%	0.38%		0.02%	0.01%	0.01%

5.4. Noise Impact

As explained in the methodology figures used were collected from marine noise modelling analysis of different real projects. Those values were then processed and a logarithmic regression was performed to obtain a function that allowed different peak SPL in dB re 1µPa to be obtained. The graph used is shown below:



As those values were stated for different pile diameters a regression analysis was needed to try to transform each WTG capacity and foundation type into their correspondent diameter. A graph representing that analysis could be seen in Appendix VI.

A summary table with the results for the different foundation and WTG could be seen below.

Table 18 Noise Impact Results Summary

	F01	F02	F03	F04	F05	F06	F07	F08	F09
WTG01	262.93	268.49	237.03	247.95	90.00	90.00	90.00	243.77	90.00
WTG02	260.32	265.73	237.03	241.09	90.00	90.00	90.00	239.45	90.00
WTG03	259.41	264.75	237.03	238.29	90.00	90.00	90.00	237.85	90.00
WTG04	258.84	264.15	237.03	236.42	90.00	90.00	90.00	236.83	90.00
WTG05	258.27	263.55	237.03	234.43	90.00	90.00	90.00	235.79	90.00
WTG06	258.16	263.43	237.03	234.03	90.00	90.00	90.00	235.58	90.00
WTG07	257.77	263.01	237.03	232.55	90.00	90.00	90.00	234.84	90.00
WTG08	257.34	262.54	237.03	230.80	90.00	90.00	90.00	234.01	90.00
WTG09	257.34	262.54	237.03	230.80	90.00	90.00	90.00	234.01	90.00
WTG10	256.40	261.54	237.03	226.60	90.00	90.00	90.00	232.15	90.00
WTG11	255.76	260.85	237.03	223.30	90.00	90.00	90.00	230.83	90.00
WTG12	254.83	259.84	237.03	217.59	90.00	90.00	90.00	228.83	90.00
WTG13	253.86	258.79	237.03	209.70	90.00	90.00	90.00	226.63	90.00
WTG14	252.60	257.42	237.03	192.52	90.00	90.00	90.00	223.56	90.00

It should be noticed here that only the peak maximum value has been analysed for the present work and therefore it has not been taken into account the likelihood of a monopile foundation pilling installation time being bigger than, for example, for a jacket piled.

5.5. Seabed Loss

As it has been explained in the methodology section figures for different WTG and foundations have been gathered from several ES and the resultant regression analysis could be seen in Appendix VII and Appendix VIII. These regressions were made to be able to translate each WTG capacity into their correspondent footprint or scour protection. This will allow to translate those figures into values for the WTG that were evaluated.

A summary table with the results for the different foundation and WTG could be seen below.

Table 19 Foundation Footprint Summary

	F01	F02	F03	F04	F05	F06	F07	F08
WTG01	79.18	134.57	535.00	56.55	615.75	3939.93	19.67	766.05
WTG02	64.41	108.06	434.93	56.55	615.75	3182.26	14.94	563.72
WTG03	59.66	99.53	402.71	56.55	615.75	2938.34	13.42	498.59
WTG04	56.82	94.42	383.43	56.55	615.75	2792.37	12.51	459.61
WTG05	54.06	89.47	364.74	56.55	615.75	2650.86	11.63	421.82
WTG06	53.54	88.52	361.17	56.55	615.75	2623.87	11.46	414.61
WTG07	51.68	85.19	348.61	56.55	615.75	2528.76	10.87	389.22
WTG08	49.65	81.55	334.85	56.55	615.75	2424.58	10.22	361.39
WTG09	49.65	81.55	334.85	56.55	615.75	2424.58	10.22	361.39
WTG10	45.43	73.96	306.20	56.55	615.75	2207.65	8.86	303.47
WTG11	42.66	68.98	287.42	56.55	615.75	2065.49	7.98	265.50
WTG12	38.78	62.01	261.10	56.55	615.75	1866.19	6.73	212.28
WTG13	34.89	55.04	234.77	56.55	615.75	1666.90	5.49	159.07
WTG14	30.14	46.50	202.56	56.55	615.75	1422.98	3.97	93.93

The best performers according to the footprint analysis were F04 and F07 both lattice structures with pined piles. It has to be taken into account that for option F04 all the figures had the same value as that was the way that it appeared in the reviewed ES. This would end up not affecting the analysis as the scour protection has more impact in the final seabed loss figure. On the other hand the worst performer was F06 as it could be expected due to GBS structures occupying a large area of the seabed when compared against the others.

Table 20 Foundation Scour Protection Summary

	F01	F02	F03	F04	F05	F06	F07	F08
WTG01	1907.67	2104.46	1724.84	602.28	1809.56	2081.69	523.37	1904.40
WTG02	1830.88	1999.47	1342.53	459.44	1809.56	1816.49	394.77	1529.09
WTG03	1806.16	1965.67	1219.46	413.46	1809.56	1731.11	353.37	1408.27
WTG04	1791.37	1945.45	1145.81	385.94	1809.56	1680.03	328.60	1335.97
WTG05	1777.03	1925.84	1074.41	359.27	1809.56	1630.49	304.58	1265.88
WTG06	1774.29	1922.10	1060.79	354.18	1809.56	1621.05	300.00	1252.51
WTG07	1764.65	1908.92	1012.80	336.25	1809.56	1587.76	283.86	1205.40
WTG08	1754.09	1894.48	960.23	316.61	1809.56	1551.29	266.17	1153.79
WTG09	1754.09	1894.48	960.23	316.61	1809.56	1551.29	266.17	1153.79
WTG10	1732.11	1864.42	850.77	275.71	1809.56	1475.36	229.36	1046.34
WTG11	1717.70	1844.72	779.04	248.91	1809.56	1425.61	205.23	975.92
WTG12	1697.50	1817.11	678.48	211.34	1809.56	1355.85	171.40	877.20
WTG13	1677.31	1789.49	577.92	173.77	1809.56	1286.09	137.57	778.49
WTG14	1652.59	1755.69	454.85	127.79	1809.56	1200.72	96.17	657.66

When analysing the scour protection for the different options options F04 and F07 still proved to be the best as. The worst performers on the other hand where F06 and F02. It is worth mentioning that F01, F02 and F05 showed very high values even for the small capacity WTG. This is a symptom of a possible data issue that could be related to the fact that some developers adopt the worst case approach and therefore give overestimated values.

Finally both footprint and scour protection values for each type of foundation were added together. These figures will be used in the final matrix to obtain the most suitable solution. From a preliminary analysis it could be said that every combination that uses F06 will be penalised in the seabed loss parameter while F04 and F06 would be benefitted from it as they had better results by a big margin.

Table 21 Foundation Footprint and Scour Protection Summary

	F01	F02	F03	F04	F05	F06	F07	F08
WTG01	1986.84	2239.04	2259.84	658.83	2425.31	6021.62	543.04	2670.45
WTG02	1895.29	2107.53	1777.46	515.99	2425.31	4998.74	409.72	2092.82
WTG03	1865.82	2065.20	1622.17	470.01	2425.31	4669.45	366.79	1906.86
WTG04	1848.19	2039.87	1529.24	442.49	2425.31	4472.40	341.11	1795.58
WTG05	1831.09	2015.30	1439.15	415.82	2425.31	4281.36	316.21	1687.70
WTG06	1827.83	2010.62	1421.96	410.73	2425.31	4244.92	311.46	1667.12
WTG07	1816.34	1994.11	1361.41	392.80	2425.31	4116.52	294.72	1594.61
WTG08	1803.75	1976.03	1295.08	373.16	2425.31	3975.87	276.39	1515.19
WTG09	1803.75	1976.03	1295.08	373.16	2425.31	3975.87	276.39	1515.19
WTG10	1777.54	1938.38	1156.97	332.26	2425.31	3683.01	238.22	1349.81
WTG11	1760.36	1913.71	1066.46	305.46	2425.31	3491.09	213.20	1241.43
WTG12	1736.28	1879.12	939.58	267.89	2425.31	3222.04	178.13	1089.49
WTG13	1712.20	1844.53	812.70	230.32	2425.31	2952.99	143.06	937.55
WTG14	1682.73	1802.19	657.40	184.34	2425.31	2623.70	100.14	751.59

5.6. LCoE Analysis

As explained in the methodology an LCoE analysis was performed to estimate how much capital could be destined to WTG and foundations. The process consisted in solve for I_1 that stands for the capital investment for the first year of operation (see Equation 3) and from that value the different CAPEX figures could be obtained. Due to the nature of the present work and the fact that those figures are very project dependent maximum and minimum values would be used.

The following graph represents the overall capital investment necessary for a project to be built according to the WTG options analysed in this work. As expected the WTG14 would be the cheapest option followed by WTG10. It stands out the fact that WTG06 is the 4th best option being the first of those WTG of over than 5MW capacity. A full version of the previous figure with a supporting table, showing values for minimum and maximum CAPEX percentages, could be seen in Appendix IX.

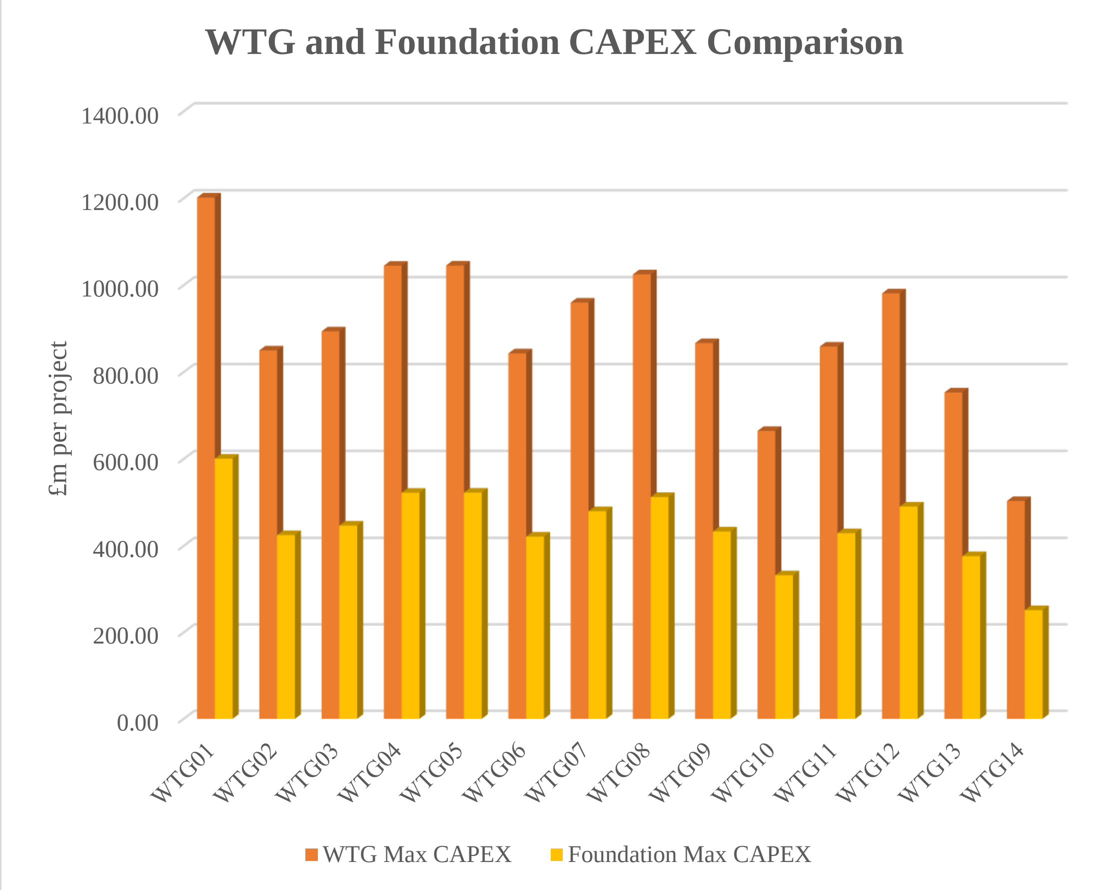


Figure 12 LCoE Capex comparison

In order to achieve the target of 100£/MWh by 2020 the CAPEX for offshore wind should be reduced in average nearly a 55%. This meaning that for the previously mentioned WTG06 option the maximum cost per WTG should be cut from £843,003 to £460,029.

5.7. Matrix Weighted Criteria

As explained in the methodology once all the impact had been analysed their outputs have been used to populate a matrix. In this section it will be shown a worked example for the WTG11 due to the fact that it has been the option that have been commissioned the most.

Table 22 WTG11 Combinations % Against The Worst Option

	% Against the worst option					
	WTG				Foundations	
	Energy Production (GWh)	CRM				
		Herring	Razorbill	Diver	Installation Noise	Seabed take
WTG11F01	47.99%	34.23%	35.40%	32.65%	4.74%	70.48%
WTG11F02	47.99%	34.23%	35.40%	32.65%	2.85%	67.81%
WTG11F03	47.99%	34.23%	35.40%	32.65%	11.72%	80.79%
WTG11F04	47.99%	34.23%	35.40%	32.65%	16.83%	94.48%
WTG11F05	47.99%	34.23%	35.40%	32.65%	66.48%	59.72%
WTG11F06	47.99%	34.23%	35.40%	32.65%	66.48%	38.84%
WTG11F07	47.99%	34.23%	35.40%	32.65%	14.03%	96.04%
WTG11F08	47.99%	34.23%	35.40%	32.65%	66.48%	77.58%

Table 23 WTG11 Combinations Performance

	Performance					
	WTG				Foundations	
	Energy Production (GWh)	CRM				
		Herring	Razorbill	Diver	Installation Noise	Seabed loss
WTG11F01	6	5	5	5	1	8
WTG11F02	6	5	5	5	1	7
WTG11F03	6	5	5	5	2	9
WTG11F04	6	5	5	5	3	10
WTG11F05	6	5	5	5	10	7
WTG11F06	6	5	5	5	10	4
WTG11F07	6	5	5	5	3	10
WTG11F08	6	5	5	5	10	8

Five different scenarios were created as a depiction of theoretical situations where one of the analysed parameters could be much more important than the others. Scenario A puts most of the importance into energy production regardless the impact on that the different combinations may cause on the environment. Scenario B gives more importance to minimise the collision mortality values and could be used for a location with high levels of sea birds of special conservation interest. Scenario C could be applied to a context where marine mammal protection was of great importance as it puts most of the importance into reducing installation noise. Scenario D on the other hand would be specific for a location where the benthic fauna is of special interest and therefore seabed loss must be minimised. Lastly scenario E tries to describe a situation where all parameters have the same impact and therefore their weights are equal. It is important to notice that in every scenario, and in order to avoid an over estimation of the CRM results, the weights for the three seabirds species act like one splitting their value according to each specie importance as stated in the methodology chapter (see Table 14).

Table 24 Analysis Weighting Factors Scenarios

	Weighting factors					
	WTG				Foundations	
Scenarios	**Energy Production (GWh)**	**Herring gull**	**Red-throated diver**	**Razorbill**	**Installation Noise**	**Seabed loss**
A	0.45	0.15	0.10	0.05	0.15	0.10
B	0.25	0.25	0.15	0.10	0.15	0.10
C	0.25	0.10	0.05	0.05	0.45	0.10
D	0.25	0.10	0.03	0.03	0.15	0.45
E	0.25	0.12	0.08	0.05	0.25	0.25

Besides the creation of the different scenarios a sensitivity analysis was performed modifying each parameter by a 15 percent to try to estimate their importance on the final value. As it can be seen in the Figure 13 below there is no much impact of the weighting factors in the maximum values of the analysis while on the contrary with regards the minimum values it could be stated seabed loss is highly affected followed by sea birds species. For the minimum values energy or electricity generation and installation noise stay practically unaffected to weighting factors changes.

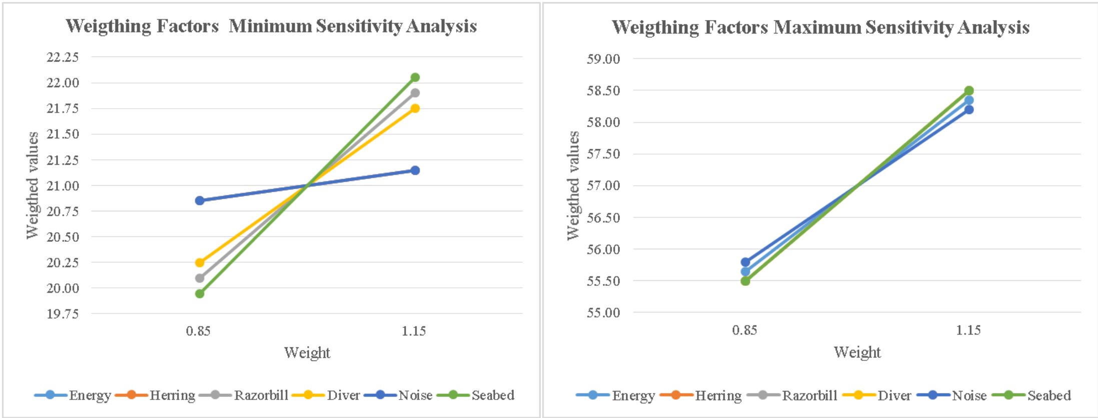


Figure 13 Weighting Factors Sensitivity Analysis

When the weighted factors for “Scenario A” are applied the final weighted values are obtained for each combination. See the example for WTG11 below.

Table 25 WTG11 Combinations Weighted Value

	Weighted value
WTG11F01	5.15
WTG11F02	5.05
WTG11F03	5.4
WTG11F04	5.65
WTG11F05	6.4
WTG11F06	6.1
WTG11F07	5.65
WTG11F08	6.5

From the previous table it could be said that F05 and F08 are the best performers for this type of WTG. This could mean that for this analysis the noise impact is very important as they are both suction foundations, jacket suction and suction bucket.

5.8. Best Solution Analysis

Data processed in the previous section was then ordered being the highest number the most suitable option in accordance to the methodology presented in this work. When applying the different weighting factors for the five scenarios stated the best options are obtained.

Table 26 10 Best Options for the Different Scenarios

Weighting A		Weighting B		Weighting C		Weighting D		Weighting E	
WTG01F05	9.7	WTG01F05	9.7	WTG01F05	9.7	WTG01F04	8.8	WTG01F05	9.25
WTG01F08	9.6	WTG01F08	9.6	WTG01F08	9.6	WTG01F07	8.8	WTG01F08	9
WTG01F06	9.1	WTG01F06	9.1	WTG05F08	9.15	WTG01F05	8.65	WTG05F08	8.75
WTG01F04	8.8	WTG01F04	8.8	WTG01F06	9.1	WTG05F08	8.55	WTG04F08	8.58
WTG01F07	8.8	WTG01F07	8.8	WTG05F05	9.05	WTG04F08	8.425	WTG05F05	8.5
WTG05F08	8.75	WTG03F05	8.7	WTG04F08	9	WTG12F08	8.275	WTG04F05	8.33
WTG05F05	8.65	WTG03F08	8.7	WTG04F05	8.9	WTG05F04	8.25	WTG03F05	8.25
WTG04F08	8.55	WTG05F08	8.55	WTG08F08	8.7	WTG05F07	8.25	WTG03F08	8.25
WTG01F03	8.5	WTG01F03	8.5	WTG09F08	8.7	WTG01F08	8.2	WTG08F08	8.25
WTG04F05	8.45	WTG05F05	8.45	WTG03F05	8.7	WTG08F08	8.15	WTG09F08	8.25

As it can be seen from the table above the best option was WTG01F05 followed closely by WTG01F08 performing best in 4 out of 5 scenarios. The first WTG alternative is WTG05F08 that appears third in 2 of the scenarios. It could be stated from what is has been observed in this and in the previous section that F05 and F08 are the overall best performers according to the limits and specific context of this analysis.

Table 27 10 Best Options after Foundation Suitability

Weighting A	
WTG01F05	8.35
WTG01F01	8.15
WTG01F02	8.15
WTG01F08	7.73
WTG01F04	7.57
WTG01F07	7.57
WTG01F06	7.54
WTG05F05	7.45
WTG01F03	7.32
WTG04F05	7.27
WTG05F08	7.04
WTG04F08	6.88
WTG05F06	6.83

If we applied the values from the foundation suitability 2.5.2.1) the results obtained are quite different with F01 and F02 going from out of the 10 best performers to the 2nd and 3rd place. It is worth mentioning that F05 is still 1st. This is mainly because despite the fact of monopiles being the best option for water depths up to 40m according to the foundation suitability section (see 2.5.2.1) jackets are benefited in this analysis by lower installation noise and seabed loss. In the following section this methodology would be validated against a Round 2 project.

Chapter 6. Results Verification

As explained in the methodology chapter data from experts would be used to evaluate the likelihood of the different options to be suitable for the project. In this chapter data from a commissioned project will be used to test the previously mentioned process and try to extrapolate the likelihood scenario that could happen in the next TCE Round 3 projects.

6.1. Round 2 Verification

Greater Gabbard offshore wind farm was selected as an example of a Round 2 development. A summarised version of its main characteristics could be seen in the table below.

Table 28 Round 2 Case Study: Greater Gabbard (sources lorc.dk and (PMSS 2005))

Status	**Commissioned**
Construction Started	**2009**
Total Installed Capacity	**500 MW**
Number of WTG	**140**
WTG Nameplate considered range	**3 – 7 MW**
WTG installed model	**SWT 3.6**
Foundations considered	**Steel Monopile, Jacket and Gravity Base**
Foundations installed	**Steel Monopile**
Wind farm extension	**147 km^2**
Distance from shore	**26 km**
Water depth	**24-34 m**

From the table above we can take every foundation option out of the validation except F01, F04 and F06. According to the WTG data gathered for this dissertation there where only to possible WTG options available for that period of construction WTG11 and WTG12. After applying Chapter 5 process the following results were obtained.

Table 29 Round 2 Verification

	Performance					
	WTG				Foundations	
	Energy Production (GWh)	Herring gull	Red-throated diver	Razorbill	Installation Noise	Seabed loss
WTG11F01	1	10	10	10	1	6
WTG11F04	1	10	10	10	2	10
WTG11F06	1	10	10	10	10	1
WTG12F01	10	1	1	1	1	6
WTG12F04	10	1	1	1	3	10
WTG12F06	10	1	1	1	10	1

	Weighted value
WTG11F01	4.2
WTG11F04	4.75
WTG11F06	5.05
WTG12F01	5.55
WTG12F04	6.25
WTG12F06	6.4

	After Foundation Suitability
WTG11F01	4.10
WTG11F04	4.09
WTG11F06	4.18
WTG12F01	5.42
WTG12F04	5.38
WTG12F06	5.30

We can observe from the performance part of the table above that CRM figures have a big impact on the analysis. Those differences are likely to come from the fact that the extrapolated max chord value for the WTG11 is more than 1m higher than for WTG12 leading to a bigger potential risk of collision. After having applied the foundation suitability values it could be stated that the best option, according to the present work methodology, would have been WTG12F04. This combination stands for a Siemens SWT-3.0 model with a jacket piled foundation. According to the Table 28 steel monopile foundations were commissioned and a SWT-3.6 WTG model used that in this analysis stands for WTG11F01. In this verification that particular solution was the second worst performer this likely to be mainly because this particular methodology does not work well when evaluating few options. In this case only two types of WTG are considered and therefore for those parameters that are only dependent on WTG characteristics there will only be one maximum and one minimum distorting the results.

6.2. Round 3 Project Extrapolation

The final goal of this work was to try to apply the methodology to a theoretical Round 3 project and the figures described in Table 1 were used.

Data from to date consented projects' DCO was gathered and used to limit the extrapolation. According to what could be seen in Table 30 below several WTG options had to be discarded. First WTG01, WTG02, WTG13 and WTG14 had to be ruled out due their nameplate capacity. Then WTG03 and WTG04 had to be rejected due to their rotor diameter being bigger than the maximum consented leaving for this final analysis options WTG05 to WTG12.

Table 30 TCE Round 3 Consented Projects Constraints for the Analysis

Parameter	WTG Capacity (MW)	Max tip height above LAT (m)	Rotor diameter (m)
Min	3	115	90
Max	8	220	164

Applying the same methodology that has been used through the present work the results obtained were summarised in the below tables.

Table 31 Round 3 Extrapolation

	Weighted value
WTG05F08	9.7
WTG05F05	9.5
WTG05F06	9.1
WTG05F04	8.8
WTG05F07	8.8
WTG05F03	8.5
WTG08F08	8.5
WTG09F08	8.5
WTG05F01	8.35
WTG08F05	8.3
WTG09F05	8.3

	After Foundation Suitability
WTG05F05	8.20
WTG05F01	8.04
WTG05F02	7.94
WTG05F08	7.78
WTG05F04	7.59
WTG05F07	7.59
WTG05F06	7.54
WTG05F03	7.34
WTG08F05	7.16
WTG09F05	7.16
WTG08F08	6.82

According to the present work the present work and after having applied the foundation suitability the best option for an average Round 3 project would be a Senvion 6.2M152 WTG with a jacket suction foundation, represented here by the combination WTG05F05.

Chapter 7. Discussion of Findings

7.1. Conclusions and Discussion

The lack of consistency in some figures obtained from the ES could have had an impact on the final outcome of the analysis. However that impact is expected to be of minor significance as it did not change the overall rank or position of any type of foundation during the sub analysis, i.e. seabed loss. This methodology has been proven to be very high dependent on the accuracy and reliability of the initial values and therefore could have benefitted from more realistic figures than those provided by developers in their technical reports. It is a clear example on how overestimation of those figures could lead to results being very different for the same type of WTG when evaluating projects carried out by different developers.

From an economic perspective the investment cost per WTG and foundation obtained from the cost analysis performed for the present work were found to be too high if the offshore wind sector is expected to achieve a GBP100/MWh LCoE in the years to come.

The present work, despite the fact of being a high-level methodology has proven a series of arguments:

- Hourly wind data provides a reliable source of information to estimate the electricity generated by a WTG.
- From a CRM point of view bigger WTG lead to less collision mortality levels mostly due to the lower number of WTG required to achieve the same output capacity.
- Any type of WTG foundation that need to be piled into the seabed should not be considered, unless mitigated, for areas with high concentrations of sensitive marine mammals.
- Scour protection plays an important role when taking into account the seabed loss but it should be balanced somehow with the potential benefit of acting as an artificial reef.
- With the current LCoE offshore wind could not compete against other sources of electricity generation without subsidiary help from the government or long term plans.

- WTG and foundation choice is highly dependent on the actual location characteristics and supply chain constraints.

The developed methodology, being aware of its limitations, is very straight forward to adapt to different locations with their different key parameters.

7.2. Further Work and Recommendations

Foundations costs could have been assessed taking into account the type and quantities of materials needed for their construction. Furthermore the impact of soil conditions into the foundation selection could be analysed to try to estimate which could be the foundation of the future according to the characteristics of North Sea seabed.

The current process could be updated when the new Upwind foundation suitability iteration had taken place with the benefits of the recently acquired insight knowledge and experience.

Wind resource analysis could benefit from a more in depth analysis of the implications of the different wind farm layouts and the impact of wind stability conditions when making electricity production estimations.

References

A2SEA, 2014. Big foundations, big challenges. *On/Off News*, (January).

Aagaard, J., 2014. Turbine foundations to be mass-produced. *On/Off News*, (January).

Ackermann, T. et al., 2005. *Evaluation of Electrical Transmission Concepts for Large Offshore Wind Farms*, Available at: http://wind.nrel.gov/public/SeaCon/Proceedings/Copenhagen.Offshore.Wind.2005/documents/papers/Grid_connection/T.Ackermann_Evaluation_of_Electrical_Transmission_Concept.pdf.

Arcus Renewable Energy Consulting Ltd, 2012. *Non-Technical Summary Beatrice Offshore Wind Farm*,

ARUP, 2011. *Review of the generation costs and deployment potential of renewable electricity technologies in the UK*, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42843/3237-cons-ro-banding-arup-report.pdf.

Band, B., 2012. *Using a Collision Risk Model to Assess Bird Collision Risks for Offshore Windfarms*, Available at: http://www.bto.org/sites/default/files/u28/downloads/Projects/Final_Report_SOSS02_Band1ModelGuidance.pdf.

Brower, M.C., 2013. *A Study of Wind Speed Variability Using Global Reanalysis Data*, Available at: https://www.awstruepower.com/assets/A-Study-of-Wind-Speed-Variability-Using-Global-Reanalysis-Data1.pdf.

Carbon Trust, 2014. DONG Energy and Carbon Trust team up to cut the costs of offshore wind. Available at: http://www.carbontrust.com/about-us/press/2014/01/dong-energy-and-carbon-trust-team-up-to-cut-the-costs-of-offshore-wind [Accessed August 1, 2014].

Collier, M.P., Japink, M. & Poot, M.J.M., 2013. *Collision rate estimates of seabirds at Neart na Gaoithe*,

Cook, A.S.C.P. et al., 2012. A review of flight heights and avoidance rates of birds in relation to offshore wind farms. , (618).

Cox, M., 2011. Wind farms could create new habitats for marine life. Available at: http://www.kentnews.co.uk/news/wind_farms_could_create_new_habitats_for_marine_life_1_1074889 [Accessed August 5, 2014].

DECC, 2013. *Digest of United Kingdom energy statistics (DUKES) 2013*, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/279523/DUKES_2013_published_version.pdf.

Det Norske Veritas, 2007. *Design of Offshore Wind Turbine Structures*,

DONG Energy, 2014. Innovative suction bucket jacket foundation hits ground bed. Available at: http://www.dongenergy.com/EN/Media/Newsroom/News/Pages/Innovative_suction_bucket_jacket_foundation_hits_ground_bed.aspx [Accessed August 1, 2014].

DONG Energy, 2006. *Non-Technical Summary Walney Offshore Wind Farm*,

DTU Aqua, 2012. Fish thriving around wind farms. Available at: http://www.aqua.dtu.dk/english/News/2012/04/120410_Fish-thriving-around-wind-farms [Accessed August 5, 2014].

EAOWL, 2012. *Environmental Statement - Chapter 8 - Underwater Noise and Vibration and Electromagnetic Fields*,

Earnest, J., 2013. *Wind power technology*, PHI Learning. Available at: http://books.google.co.uk/books?id=Ir9nAgAAQBAJ.

Ernst & Young, 2009. *Cost of and financial support for offshore wind*, Available at: http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file51142.pdf.

EWEA, 2012. *Positive environmental impacts of offshore wind farms*,

EWEA, 2009. Wind Energy. The Facts. , p.32.

EWEA, 2011. *Wind in our sails*,

Furness, R.W., Wade, H.M. & Masden, E. a, 2013. Assessing vulnerability of marine bird populations to offshore wind farms. *Journal of environmental management*, 119, pp.56–66. Available at: http://www.ncbi.nlm.nih.gov/pubmed/23454414 [Accessed July 9, 2014].

Gellatly, B., 2014. *Offshore wind - is £100/MWh by 2020 still possible?*, Available at: https://www.carbontrust.com/media/508349/Carbon-Trust-OWA-All-Energy-2014-Breanne-Gelattly.pdf.

Greenacre, P., 2013. *UKERC Technology and Policy Assessment Cost Methodologies Project : Offshore Wind Case Study Working Paper*,

GWFL, 2011a. *Environmental Statement - Chapter 14: Marine Mammals*,

GWFL, 2011b. *Environmental Statement - Technical Appendices 2 - Ornithological Technical Report - 11.A*,

Heptonstall, P. et al., 2012. The cost of offshore wind: Understanding the past and projecting the future. *Energy Policy*, 41, pp.815–821. Available at:

http://linkinghub.elsevier.com/retrieve/pii/S030142151100944X [Accessed August 18, 2014].

IAIA and IEA, 1999. Principles of Environmental Impact Assessment Best Practice. *Special Publication Series*.

Infrastructure Planning, 2014. *EAOWL Development Consent Order as made by the Secretary of State for Energy and Climate Change*, Available at: http://infrastructure.planningportal.gov.uk/document/2550703.

Maclean, I.M.D. et al., 2009. *A Review of Assessment Methodologies for Offshore Windfarms*, Available at: http://www.thecrownestate.co.uk/media/5884/2009-05 A review of assessment methodologies for offshore windfarms.pdf.

Mainstream Renewable Power, 2012. *Non-Technical Summary Neart na Gaoithe Offshore Wind Farm*,

Morgan, R.K., 1998. *Environmental Impact Assessment: A Methodological Approach*,

Mott MacDonald, 2011. *Costs of low carbon generation technologies*, Available at: http://archive.theccc.org.uk/aws/Renewables Review/CCC_Chapter 2.pdf.

Nehls, G. et al., 2007. *Assessment and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from the construction of offshore windfarms*,

Newman, J. & Klein, P., 2014. The Impacts of Atmospheric Stability on the Accuracy of Wind Speed Extrapolation Methods. *Resources*, 3(1), pp.81–105. Available at: http://www.mdpi.com/2079-9276/3/1/81/ [Accessed August 12, 2014].

Ortolano, L. & Shepherd, A., 1995. Environmental Impact Assessment: Challenges and Opportunities. *Impact Assessment*, 13(1), pp.3–30. Available at: http://dx.doi.org/10.1080/07349165.1995.9726076.

Parwin, S.J., Nedwell, J.E. & Workman, R., 2006. *Underwater noise impact modelling in support of the London Array, Greater Gabbard and Thanet offshore wind farm developments. Subacoustech Report No. 710R0515*,

Pelastar, 2013. *Making Offshore Wind an Economic Reality*,

Planning Inspectorate, 2012. Advice Note 9. Using the “Rochdale Envelope.”

PMSS, 2005. *Non-Technical Summary Greater Gabbard Offshore Wind Farm*,

Principle, 2013. *WindFloat The Offshore Wind Solution*,

REUTERS, 2011. North Sea platforms are fish magnets: researcher. Available at: http://www.reuters.com/article/2011/09/29/us-north-sea-fish-idUSTRE78S1SH20110929 [Accessed August 5, 2014].

Shearer, K., 2013. *Assessment of cumulative impacts in offshore wind developments*.

Sørensen, T., Nielsen, P. & Thøgersen, M.L., 2006. *Recalibrating Wind Turbine Wake Models – Validating the Wake Model Performance for Large Offshore Wind Farms*, Available at: http://docs.wind-watch.org/wake-0693_Ewec2006fullpaper.pdf.

TCE, 2012. *Rochdale Envelope Workshop - Wave and Tidal*,

Tempel, J. Van Der, Zaaijer, M.B. & Subroto, H., 2005. The effects of Scour on the design of Offshore Wind Turbines. , (2000).

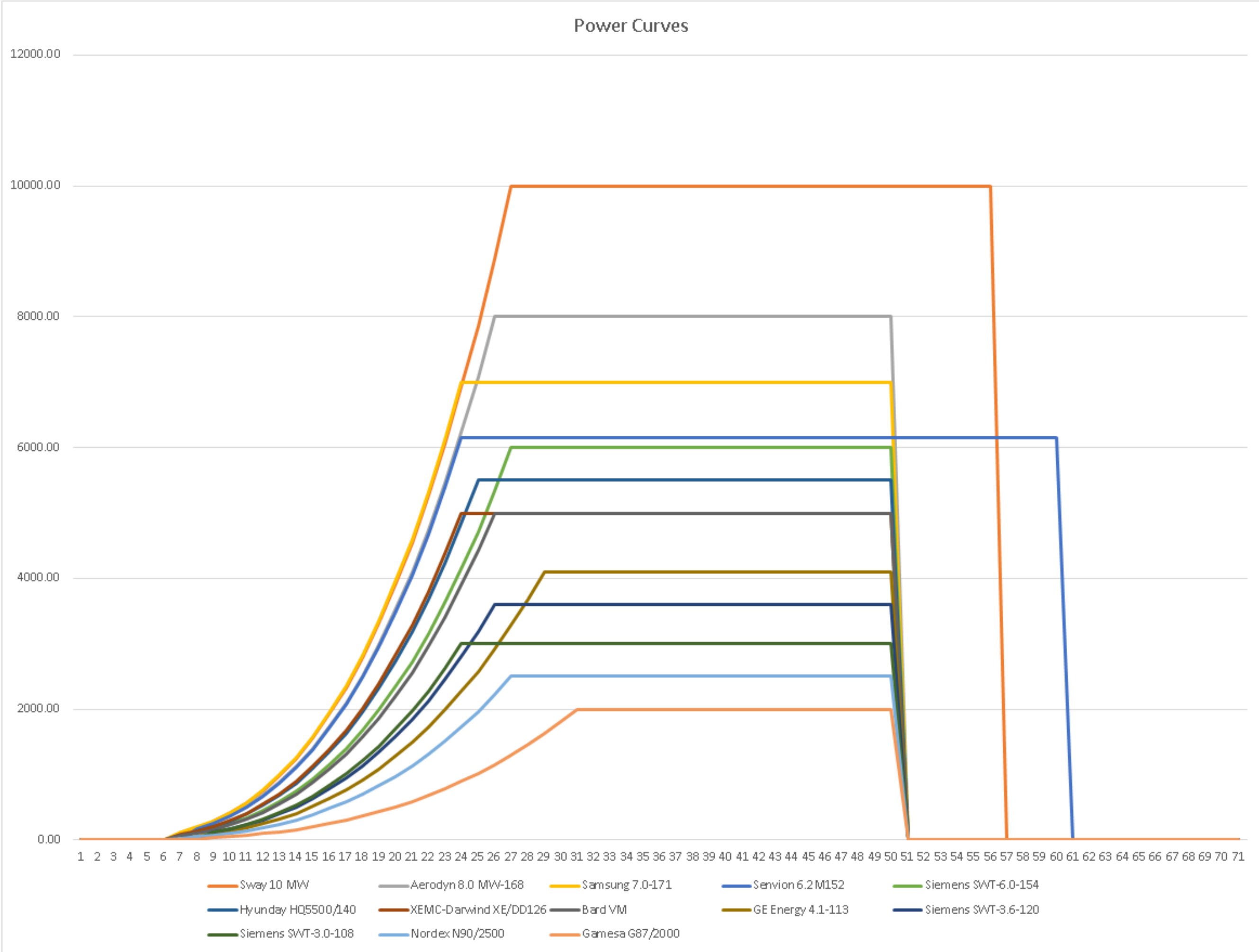
The Crown Estate, 2012. *Offshore Wind Cost Reduction Pathways Study*, Available at: http://www.thecrownestate.co.uk/media/5493/ei-offshore-wind-cost-reduction-pathways-study.pdf.

De Villiers, P., 2012. *Demonstrating Keystone Engineering's innovative Inward Battered Guide Structure (IBGS) offshore foundation concept at Hornsea*, Available at: https://www.carbontrust.com/media/105310/foundations_presentation-2apr12-pdv.pdf.

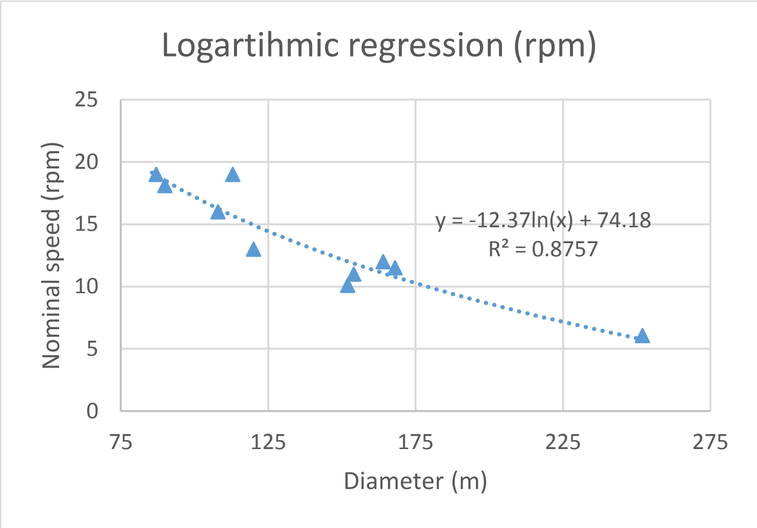
De Vries, W.E., 2007. *Upwind WP4 D4.2.1 Assessment of bottom-mounted support structure types with conventional design stiffness and installation techniques for typical deep water sites*,

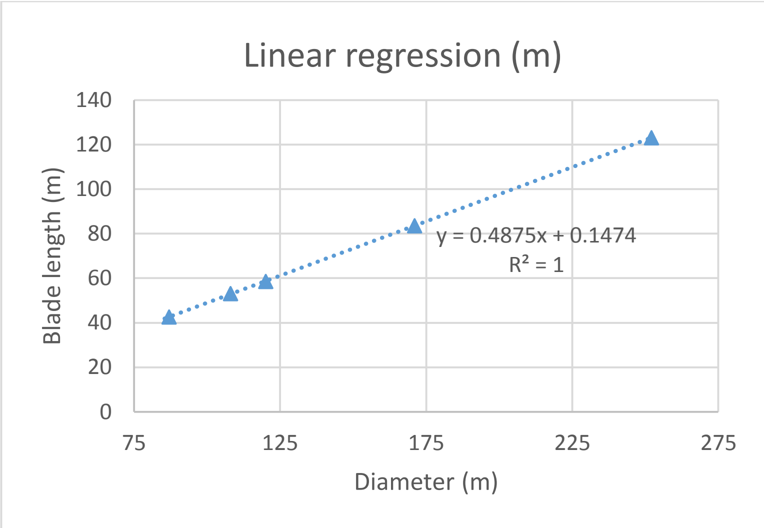
Wilhelmsson, D. et al., 2010. *Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy*, Available at: http://cmsdata.iucn.org/downloads/2010_014.pdf.

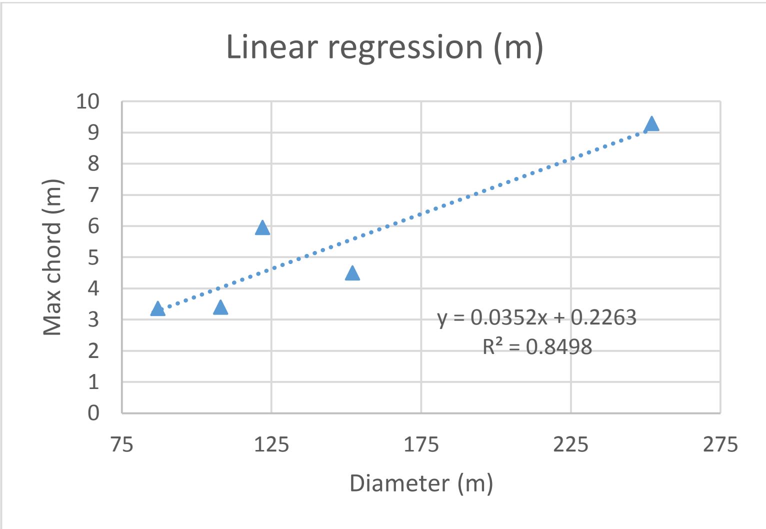
Appendix I. **WTG Power Curves**



Appendix II. **WTG Inputs Regressions**







Appendix III. Solution Analysis

	WTG				Foundations	
	Energy Production (GWh)	Herring gull	Red-throated diver	Razorbill	Installation Noise	Seabed loss
WTG01F01	47,539.26	0.25%	0.08%	0.09%	262.93	1,986.84
WTG01F02	47,539.26	0.25%	0.08%	0.09%	268.49	2,239.04
WTG01F03	47,539.26	0.25%	0.08%	0.09%	237.03	2,259.84
WTG01F04	47,539.26	0.25%	0.08%	0.09%	247.95	658.83
WTG01F05	47,539.26	0.25%	0.08%	0.09%	90.00	2,425.31
WTG01F06	47,539.26	0.25%	0.08%	0.09%	90.00	6,021.62
WTG01F07	47,539.26	0.25%	0.08%	0.09%	243.77	543.04
WTG01F08	47,539.26	0.25%	0.08%	0.09%	90.00	2,670.45
WTG02F01	36,597.73	0.34%	0.11%	0.12%	260.32	1,895.29
WTG02F02	36,597.73	0.34%	0.11%	0.12%	265.73	2,107.53
WTG02F03	36,597.73	0.34%	0.11%	0.12%	237.03	1,777.46
WTG02F04	36,597.73	0.34%	0.11%	0.12%	241.09	515.99
WTG02F05	36,597.73	0.34%	0.11%	0.12%	90.00	2,425.31
WTG02F06	36,597.73	0.34%	0.11%	0.12%	90.00	4,998.74
WTG02F07	36,597.73	0.34%	0.11%	0.12%	239.45	409.72
WTG02F08	36,597.73	0.34%	0.11%	0.12%	90.00	2,092.82
WTG03F01	37,585.47	0.30%	0.10%	0.10%	259.41	1,865.82
WTG03F02	37,585.47	0.30%	0.10%	0.10%	264.75	2,065.20
WTG03F03	37,585.47	0.30%	0.10%	0.10%	237.03	1,622.17
WTG03F04	37,585.47	0.30%	0.10%	0.10%	238.29	470.01
WTG03F05	37,585.47	0.30%	0.10%	0.10%	90.00	2,425.31
WTG03F06	37,585.47	0.30%	0.10%	0.10%	90.00	4,669.45
WTG03F07	37,585.47	0.30%	0.10%	0.10%	237.85	366.79
WTG03F08	37,585.47	0.30%	0.10%	0.10%	90.00	1,906.86
WTG04F01	43,099.77	0.59%	0.17%	0.18%	258.84	1,848.19
WTG04F02	43,099.77	0.59%	0.17%	0.18%	264.15	2,039.87
WTG04F03	43,099.77	0.59%	0.17%	0.18%	237.03	1,529.24
WTG04F04	43,099.77	0.59%	0.17%	0.18%	236.42	442.49
WTG04F05	43,099.77	0.59%	0.17%	0.18%	90.00	2,425.31
WTG04F06	43,099.77	0.59%	0.17%	0.18%	90.00	4,472.40
WTG04F07	43,099.77	0.59%	0.17%	0.18%	236.83	341.11
WTG04F08	43,099.77	0.59%	0.17%	0.18%	90.00	1,795.58
WTG05F01	43,390.50	0.45%	0.15%	0.15%	258.27	1,831.09
WTG05F02	43,390.50	0.45%	0.15%	0.15%	263.55	2,015.30
WTG05F03	43,390.50	0.45%	0.15%	0.15%	237.03	1,439.15
WTG05F04	43,390.50	0.45%	0.15%	0.15%	234.43	415.82
WTG05F05	43,390.50	0.45%	0.15%	0.15%	90.00	2,425.31
WTG05F06	43,390.50	0.45%	0.15%	0.15%	90.00	4,281.36

WTG05F07	43,390.50	0.45%	0.15%	0.15%	235.79	316.21
WTG05F08	43,390.50	0.45%	0.15%	0.15%	90.00	1,687.70
WTG06F01	35,877.02	0.54%	0.18%	0.19%	258.16	1,827.83
WTG06F02	35,877.02	0.54%	0.18%	0.19%	263.43	2,010.62
WTG06F03	35,877.02	0.54%	0.18%	0.19%	237.03	1,421.96
WTG06F04	35,877.02	0.54%	0.18%	0.19%	234.03	410.73
WTG06F05	35,877.02	0.54%	0.18%	0.19%	90.00	2,425.31
WTG06F06	35,877.02	0.54%	0.18%	0.19%	90.00	4,244.92
WTG06F07	35,877.02	0.54%	0.18%	0.19%	235.58	311.46
WTG06F08	35,877.02	0.54%	0.18%	0.19%	90.00	1,667.12
WTG07F01	40,152.93	0.57%	0.19%	0.20%	257.77	1,816.34
WTG07F02	40,152.93	0.57%	0.19%	0.20%	263.01	1,994.11
WTG07F03	40,152.93	0.57%	0.19%	0.20%	237.03	1,361.41
WTG07F04	40,152.93	0.57%	0.19%	0.20%	232.55	392.80
WTG07F05	40,152.93	0.57%	0.19%	0.20%	90.00	2,425.31
WTG07F06	40,152.93	0.57%	0.19%	0.20%	90.00	4,116.52
WTG07F07	40,152.93	0.57%	0.19%	0.20%	234.84	294.72
WTG07F08	40,152.93	0.57%	0.19%	0.20%	90.00	1,594.61
WTG08F01	42,629.35	0.59%	0.20%	0.20%	257.34	1,803.75
WTG08F02	42,629.35	0.59%	0.20%	0.20%	262.54	1,976.03
WTG08F03	42,629.35	0.59%	0.20%	0.20%	237.03	1,295.08
WTG08F04	42,629.35	0.59%	0.20%	0.20%	230.80	373.16
WTG08F05	42,629.35	0.59%	0.20%	0.20%	90.00	2,425.31
WTG08F06	42,629.35	0.59%	0.20%	0.20%	90.00	3,975.87
WTG08F07	42,629.35	0.59%	0.20%	0.20%	234.01	276.39
WTG08F08	42,629.35	0.59%	0.20%	0.20%	90.00	1,515.19
WTG09F01	42,629.35	0.59%	0.20%	0.20%	257.34	1,803.75
WTG09F02	42,629.35	0.59%	0.20%	0.20%	262.54	1,976.03
WTG09F03	42,629.35	0.59%	0.20%	0.20%	237.03	1,295.08
WTG09F04	42,629.35	0.59%	0.20%	0.20%	230.80	373.16
WTG09F05	42,629.35	0.59%	0.20%	0.20%	90.00	2,425.31
WTG09F06	42,629.35	0.59%	0.20%	0.20%	90.00	3,975.87
WTG09F07	42,629.35	0.59%	0.20%	0.20%	234.01	276.39
WTG09F08	42,629.35	0.59%	0.20%	0.20%	90.00	1,515.19
WTG10F01	30,192.91	0.70%	0.24%	0.24%	256.40	1,803.75
WTG10F02	30,192.91	0.70%	0.24%	0.24%	261.54	1,976.03
WTG10F03	30,192.91	0.70%	0.24%	0.24%	237.03	1,295.08
WTG10F04	30,192.91	0.70%	0.24%	0.24%	226.60	373.16
WTG10F05	30,192.91	0.70%	0.24%	0.24%	90.00	2,425.31
WTG10F06	30,192.91	0.70%	0.24%	0.24%	90.00	3,975.87
WTG10F07	30,192.91	0.70%	0.24%	0.24%	232.15	276.39
WTG10F08	30,192.91	0.70%	0.24%	0.24%	90.00	1,515.19
WTG11F01	36,510.12	0.76%	0.25%	0.26%	255.76	1,777.54
WTG11F02	36,510.12	0.76%	0.25%	0.26%	260.85	1,938.38
WTG11F03	36,510.12	0.76%	0.25%	0.26%	237.03	1,156.97

WTG11F04	36,510.12	0.76%	0.25%	0.26%	223.30	332.26
WTG11F05	36,510.12	0.76%	0.25%	0.26%	90.00	2,425.31
WTG11F06	36,510.12	0.76%	0.25%	0.26%	90.00	3,683.01
WTG11F07	36,510.12	0.76%	0.25%	0.26%	230.83	238.22
WTG11F08	36,510.12	0.76%	0.25%	0.26%	90.00	1,349.81
WTG12F01	40,844.13	0.79%	0.27%	0.26%	254.83	1,760.36
WTG12F02	40,844.13	0.79%	0.27%	0.26%	259.84	1,913.71
WTG12F03	40,844.13	0.79%	0.27%	0.26%	237.03	1,066.46
WTG12F04	40,844.13	0.79%	0.27%	0.26%	217.59	305.46
WTG12F05	40,844.13	0.79%	0.27%	0.26%	90.00	2,425.31
WTG12F06	40,844.13	0.79%	0.27%	0.26%	90.00	3,491.09
WTG12F07	40,844.13	0.79%	0.27%	0.26%	228.83	213.20
WTG12F08	40,844.13	0.79%	0.27%	0.26%	90.00	1,241.43
WTG13F01	33,123.99	0.95%	0.32%	0.32%	253.86	1,736.28
WTG13F02	33,123.99	0.95%	0.32%	0.32%	258.79	1,879.12
WTG13F03	33,123.99	0.95%	0.32%	0.32%	237.03	939.58
WTG13F04	33,123.99	0.95%	0.32%	0.32%	209.70	267.89
WTG13F05	33,123.99	0.95%	0.32%	0.32%	90.00	2,425.31
WTG13F06	33,123.99	0.95%	0.32%	0.32%	90.00	3,222.04
WTG13F07	33,123.99	0.95%	0.32%	0.32%	226.63	178.13
WTG13F08	33,123.99	0.95%	0.32%	0.32%	90.00	1,089.49
WTG14F01	24,670.36	1.15%	0.39%	0.38%	252.60	1,712.20
WTG14F02	24,670.36	1.15%	0.39%	0.38%	257.42	1,844.53
WTG14F03	24,670.36	1.15%	0.39%	0.38%	237.03	812.70
WTG14F04	24,670.36	1.15%	0.39%	0.38%	192.52	230.32
WTG14F05	24,670.36	1.15%	0.39%	0.38%	90.00	2,425.31
WTG14F06	24,670.36	1.15%	0.39%	0.38%	90.00	2,952.99
WTG14F07	24,670.36	1.15%	0.39%	0.38%	223.56	143.06
WTG14F08	24,670.36	1.15%	0.39%	0.38%	90.00	937.55

	% Against the worst option					
	WTG				Foundations	
	Energy Production (GWh)	Herring gull	Red-throated diver	Razorbill	Installation Noise	Seabed loss
WTG01F01	92.70%	78.43%	79.37%	76.58%	2.07%	67.00%
WTG01F02	92.70%	78.43%	79.37%	76.58%	0.00%	62.82%
WTG01F03	92.70%	78.43%	79.37%	76.58%	11.72%	62.47%
WTG01F04	92.70%	78.43%	79.37%	76.58%	7.65%	89.06%
WTG01F05	92.70%	78.43%	79.37%	76.58%	66.48%	59.72%
WTG01F06	92.70%	78.43%	79.37%	76.58%	66.48%	0.00%
WTG01F07	92.70%	78.43%	79.37%	76.58%	9.21%	90.98%
WTG01F08	92.70%	78.43%	79.37%	76.58%	66.48%	55.65%
WTG02F01	48.35%	70.42%	70.90%	68.86%	3.04%	68.53%
WTG02F02	48.35%	70.42%	70.90%	68.86%	1.03%	65.00%
WTG02F03	48.35%	70.42%	70.90%	68.86%	11.72%	70.48%
WTG02F04	48.35%	70.42%	70.90%	68.86%	10.21%	91.43%
WTG02F05	48.35%	70.42%	70.90%	68.86%	66.48%	59.72%
WTG02F06	48.35%	70.42%	70.90%	68.86%	66.48%	16.99%
WTG02F07	48.35%	70.42%	70.90%	68.86%	10.82%	93.20%
WTG02F08	48.35%	70.42%	70.90%	68.86%	66.48%	65.24%
WTG03F01	52.35%	73.87%	74.35%	72.59%	3.38%	69.01%
WTG03F02	52.35%	73.87%	74.35%	72.59%	1.39%	65.70%
WTG03F03	52.35%	73.87%	74.35%	72.59%	11.72%	73.06%
WTG03F04	52.35%	73.87%	74.35%	72.59%	11.25%	92.19%
WTG03F05	52.35%	73.87%	74.35%	72.59%	66.48%	59.72%
WTG03F06	52.35%	73.87%	74.35%	72.59%	66.48%	22.46%
WTG03F07	52.35%	73.87%	74.35%	72.59%	11.41%	93.91%
WTG03F08	52.35%	73.87%	74.35%	72.59%	66.48%	68.33%
WTG04F01	74.70%	48.26%	55.69%	52.20%	3.59%	69.31%
WTG04F02	74.70%	48.26%	55.69%	52.20%	1.62%	66.12%
WTG04F03	74.70%	48.26%	55.69%	52.20%	11.72%	74.60%
WTG04F04	74.70%	48.26%	55.69%	52.20%	11.94%	92.65%
WTG04F05	74.70%	48.26%	55.69%	52.20%	66.48%	59.72%
WTG04F06	74.70%	48.26%	55.69%	52.20%	66.48%	25.73%
WTG04F07	74.70%	48.26%	55.69%	52.20%	11.79%	94.34%
WTG04F08	74.70%	48.26%	55.69%	52.20%	66.48%	70.18%
WTG05F01	75.88%	60.80%	61.89%	59.81%	3.80%	69.59%
WTG05F02	75.88%	60.80%	61.89%	59.81%	1.84%	66.53%
WTG05F03	75.88%	60.80%	61.89%	59.81%	11.72%	76.10%
WTG05F04	75.88%	60.80%	61.89%	59.81%	12.68%	93.09%
WTG05F05	75.88%	60.80%	61.89%	59.81%	66.48%	59.72%

WTG05F06	75.88%	60.80%	61.89%	59.81%	66.48%	28.90%
WTG05F07	75.88%	60.80%	61.89%	59.81%	12.18%	94.75%
WTG05F08	75.88%	60.80%	61.89%	59.81%	66.48%	71.97%
WTG06F01	45.43%	52.95%	53.65%	50.71%	3.85%	69.65%
WTG06F02	45.43%	52.95%	53.65%	50.71%	1.88%	66.61%
WTG06F03	45.43%	52.95%	53.65%	50.71%	11.72%	76.39%
WTG06F04	45.43%	52.95%	53.65%	50.71%	12.83%	93.18%
WTG06F05	45.43%	52.95%	53.65%	50.71%	66.48%	59.72%
WTG06F06	45.43%	52.95%	53.65%	50.71%	66.48%	29.51%
WTG06F07	45.43%	52.95%	53.65%	50.71%	12.26%	94.83%
WTG06F08	45.43%	52.95%	53.65%	50.71%	66.48%	72.31%
WTG07F01	62.76%	50.26%	51.00%	48.35%	3.99%	69.84%
WTG07F02	62.76%	50.26%	51.00%	48.35%	2.04%	66.88%
WTG07F03	62.76%	50.26%	51.00%	48.35%	11.72%	77.39%
WTG07F04	62.76%	50.26%	51.00%	48.35%	13.39%	93.48%
WTG07F05	62.76%	50.26%	51.00%	48.35%	66.48%	59.72%
WTG07F06	62.76%	50.26%	51.00%	48.35%	66.48%	31.64%
WTG07F07	62.76%	50.26%	51.00%	48.35%	12.53%	95.11%
WTG07F08	62.76%	50.26%	51.00%	48.35%	66.48%	73.52%
WTG08F01	72.80%	48.21%	49.11%	46.70%	4.15%	70.05%
WTG08F02	72.80%	48.21%	49.11%	46.70%	2.21%	67.18%
WTG08F03	72.80%	48.21%	49.11%	46.70%	11.72%	78.49%
WTG08F04	72.80%	48.21%	49.11%	46.70%	14.04%	93.80%
WTG08F05	72.80%	48.21%	49.11%	46.70%	66.48%	59.72%
WTG08F06	72.80%	48.21%	49.11%	46.70%	66.48%	33.97%
WTG08F07	72.80%	48.21%	49.11%	46.70%	12.84%	95.41%
WTG08F08	72.80%	48.21%	49.11%	46.70%	66.48%	74.84%
WTG09F01	72.80%	48.21%	49.11%	46.70%	4.15%	70.05%
WTG09F02	72.80%	48.21%	49.11%	46.70%	2.21%	67.18%
WTG09F03	72.80%	48.21%	49.11%	46.70%	11.72%	78.49%
WTG09F04	72.80%	48.21%	49.11%	46.70%	14.04%	93.80%
WTG09F05	72.80%	48.21%	49.11%	46.70%	66.48%	59.72%
WTG09F06	72.80%	48.21%	49.11%	46.70%	66.48%	33.97%
WTG09F07	72.80%	48.21%	49.11%	46.70%	12.84%	95.41%
WTG09F08	72.80%	48.21%	49.11%	46.70%	66.48%	74.84%
WTG10F01	22.39%	38.67%	38.44%	37.66%	4.50%	70.05%
WTG10F02	22.39%	38.67%	38.44%	37.66%	2.59%	67.18%
WTG10F03	22.39%	38.67%	38.44%	37.66%	11.72%	78.49%
WTG10F04	22.39%	38.67%	38.44%	37.66%	15.60%	93.80%
WTG10F05	22.39%	38.67%	38.44%	37.66%	66.48%	59.72%
WTG10F06	22.39%	38.67%	38.44%	37.66%	66.48%	33.97%
WTG10F07	22.39%	38.67%	38.44%	37.66%	13.54%	95.41%
WTG10F08	22.39%	38.67%	38.44%	37.66%	66.48%	74.84%
WTG11F01	47.99%	34.23%	35.40%	32.65%	4.74%	70.48%

WTG11F02	47.99%	34.23%	35.40%	32.65%	2.85%	67.81%
WTG11F03	47.99%	34.23%	35.40%	32.65%	11.72%	80.79%
WTG11F04	47.99%	34.23%	35.40%	32.65%	16.83%	94.48%
WTG11F05	47.99%	34.23%	35.40%	32.65%	66.48%	59.72%
WTG11F06	47.99%	34.23%	35.40%	32.65%	66.48%	38.84%
WTG11F07	47.99%	34.23%	35.40%	32.65%	14.03%	96.04%
WTG11F08	47.99%	34.23%	35.40%	32.65%	66.48%	77.58%
WTG12F01	65.56%	31.52%	31.33%	31.47%	5.09%	70.77%
WTG12F02	65.56%	31.52%	31.33%	31.47%	3.22%	68.22%
WTG12F03	65.56%	31.52%	31.33%	31.47%	11.72%	82.29%
WTG12F04	65.56%	31.52%	31.33%	31.47%	18.96%	94.93%
WTG12F05	65.56%	31.52%	31.33%	31.47%	66.48%	59.72%
WTG12F06	65.56%	31.52%	31.33%	31.47%	66.48%	42.02%
WTG12F07	65.56%	31.52%	31.33%	31.47%	14.77%	96.46%
WTG12F08	65.56%	31.52%	31.33%	31.47%	66.48%	79.38%
WTG13F01	34.27%	17.12%	18.90%	17.22%	5.45%	71.17%
WTG13F02	34.27%	17.12%	18.90%	17.22%	3.61%	68.79%
WTG13F03	34.27%	17.12%	18.90%	17.22%	11.72%	84.40%
WTG13F04	34.27%	17.12%	18.90%	17.22%	21.89%	95.55%
WTG13F05	34.27%	17.12%	18.90%	17.22%	66.48%	59.72%
WTG13F06	34.27%	17.12%	18.90%	17.22%	66.48%	46.49%
WTG13F07	34.27%	17.12%	18.90%	17.22%	15.59%	97.04%
WTG13F08	34.27%	17.12%	18.90%	17.22%	66.48%	81.91%
WTG14F01	0.00%	0.00%	0.00%	0.00%	5.92%	71.57%
WTG14F02	0.00%	0.00%	0.00%	0.00%	4.12%	69.37%
WTG14F03	0.00%	0.00%	0.00%	0.00%	11.72%	86.50%
WTG14F04	0.00%	0.00%	0.00%	0.00%	28.29%	96.18%
WTG14F05	0.00%	0.00%	0.00%	0.00%	66.48%	59.72%
WTG14F06	0.00%	0.00%	0.00%	0.00%	66.48%	50.96%
WTG14F07	0.00%	0.00%	0.00%	0.00%	16.73%	97.62%
WTG14F08	0.00%	0.00%	0.00%	0.00%	66.48%	84.43%

	Intervals of performance					
	WTG				Foundations	
	Energy Production (GWh)	Herring gull	Red-throated diver	Razorbill	Installation Noise	Seabed loss
Very High	83.43%	70.59%	71.44%	68.92%	59.83%	87.86%
	74.16%	62.75%	63.50%	61.26%	53.18%	78.10%
High	64.89%	54.90%	55.56%	53.61%	46.54%	68.34%
	55.62%	47.06%	47.62%	45.95%	39.89%	58.57%
Average	46.35%	39.22%	39.69%	38.29%	33.24%	48.81%
	37.08%	31.37%	31.75%	30.63%	26.59%	39.05%
Poor	27.81%	23.53%	23.81%	22.97%	19.94%	29.29%
	18.54%	15.69%	15.87%	15.32%	13.30%	19.52%
Very Poor	9.27%	7.84%	7.94%	7.66%	6.65%	9.76%
	0%	0%	0%	0%	0%	0%

	Performance					
	WTG				Foundations	
	Energy Production (GWh)	Herring gull	Red-throated diver	Razorbill	Installation Noise	Seabed loss
WTG01F01	10	10	10	10	1	7
WTG01F02	10	10	10	10	1	7
WTG01F03	10	10	10	10	2	7
WTG01F04	10	10	10	10	2	10
WTG01F05	10	10	10	10	10	7
WTG01F06	10	10	10	10	10	1
WTG01F07	10	10	10	10	2	10
WTG01F08	10	10	10	10	10	6
WTG02F01	6	9	9	9	1	8
WTG02F02	6	9	9	9	1	7
WTG02F03	6	9	9	9	2	8
WTG02F04	6	9	9	9	2	10
WTG02F05	6	9	9	9	10	7
WTG02F06	6	9	9	9	10	2
WTG02F07	6	9	9	9	2	10
WTG02F08	6	9	9	9	10	7
WTG03F01	6	10	10	10	1	8
WTG03F02	6	10	10	10	1	7
WTG03F03	6	10	10	10	2	8
WTG03F04	6	10	10	10	2	10
WTG03F05	6	10	10	10	10	7
WTG03F06	6	10	10	10	10	3
WTG03F07	6	10	10	10	2	10
WTG03F08	6	10	10	10	10	7
WTG04F01	9	7	8	7	1	8
WTG04F02	9	7	8	7	1	7
WTG04F03	9	7	8	7	2	8
WTG04F04	9	7	8	7	2	10
WTG04F05	9	7	8	7	10	7
WTG04F06	9	7	8	7	10	3
WTG04F07	9	7	8	7	2	10
WTG04F08	9	7	8	7	10	8
WTG05F01	9	8	8	8	1	8
WTG05F02	9	8	8	8	1	7
WTG05F03	9	8	8	8	2	8
WTG05F04	9	8	8	8	2	10
WTG05F05	9	8	8	8	10	7

WTG05F06	9	8	8	8	10	3
WTG05F07	9	8	8	8	2	10
WTG05F08	9	8	8	8	10	8
WTG06F01	5	7	7	7	1	8
WTG06F02	5	7	7	7	1	7
WTG06F03	5	7	7	7	2	8
WTG06F04	5	7	7	7	2	10
WTG06F05	5	7	7	7	10	7
WTG06F06	5	7	7	7	10	4
WTG06F07	5	7	7	7	2	10
WTG06F08	5	7	7	7	10	8
WTG07F01	7	7	7	7	1	8
WTG07F02	7	7	7	7	1	7
WTG07F03	7	7	7	7	2	8
WTG07F04	7	7	7	7	3	10
WTG07F05	7	7	7	7	10	7
WTG07F06	7	7	7	7	10	4
WTG07F07	7	7	7	7	2	10
WTG07F08	7	7	7	7	10	8
WTG08F01	8	7	7	7	1	8
WTG08F02	8	7	7	7	1	7
WTG08F03	8	7	7	7	2	9
WTG08F04	8	7	7	7	3	10
WTG08F05	8	7	7	7	10	7
WTG08F06	8	7	7	7	10	4
WTG08F07	8	7	7	7	2	10
WTG08F08	8	7	7	7	10	8
WTG09F01	8	7	7	7	1	8
WTG09F02	8	7	7	7	1	7
WTG09F03	8	7	7	7	2	9
WTG09F04	8	7	7	7	3	10
WTG09F05	8	7	7	7	10	7
WTG09F06	8	7	7	7	10	4
WTG09F07	8	7	7	7	2	10
WTG09F08	8	7	7	7	10	8
WTG10F01	3	5	5	5	1	8
WTG10F02	3	5	5	5	1	7
WTG10F03	3	5	5	5	2	9
WTG10F04	3	5	5	5	3	10
WTG10F05	3	5	5	5	10	7
WTG10F06	3	5	5	5	10	4
WTG10F07	3	5	5	5	3	10
WTG10F08	3	5	5	5	10	8
WTG11F01	6	5	5	5	1	8

WTG11F02	6	5	5	5	1	7
WTG11F03	6	5	5	5	2	9
WTG11F04	6	5	5	5	3	10
WTG11F05	6	5	5	5	10	7
WTG11F06	6	5	5	5	10	4
WTG11F07	6	5	5	5	3	10
WTG11F08	6	5	5	5	10	8
WTG12F01	8	5	4	5	1	8
WTG12F02	8	5	4	5	1	7
WTG12F03	8	5	4	5	2	9
WTG12F04	8	5	4	5	3	10
WTG12F05	8	5	4	5	10	7
WTG12F06	8	5	4	5	10	5
WTG12F07	8	5	4	5	3	10
WTG12F08	8	5	4	5	10	9
WTG13F01	4	3	3	3	1	8
WTG13F02	4	3	3	3	1	8
WTG13F03	4	3	3	3	2	9
WTG13F04	4	3	3	3	4	10
WTG13F05	4	3	3	3	10	7
WTG13F06	4	3	3	3	10	5
WTG13F07	4	3	3	3	3	10
WTG13F08	4	3	3	3	10	9
WTG14F01	1	1	1	1	1	8
WTG14F02	1	1	1	1	1	8
WTG14F03	1	1	1	1	2	9
WTG14F04	1	1	1	1	5	10
WTG14F05	1	1	1	1	10	7
WTG14F06	1	1	1	1	10	6
WTG14F07	1	1	1	1	3	10
WTG14F08	1	1	1	1	10	9

	Weighted value
WTG01F01	8.35
WTG01F02	8.35
WTG01F03	8.5
WTG01F04	8.8
WTG01F05	9.7
WTG01F06	9.1
WTG01F07	8.8
WTG01F08	9.6
WTG02F01	6.35
WTG02F02	6.25
WTG02F03	6.5
WTG02F04	6.7
WTG02F05	7.6
WTG02F06	7.1
WTG02F07	6.7
WTG02F08	7.6
WTG03F01	6.65
WTG03F02	6.55
WTG03F03	6.8
WTG03F04	7
WTG03F05	7.9
WTG03F06	7.5
WTG03F07	7
WTG03F08	7.9
WTG04F01	7.2
WTG04F02	7.1
WTG04F03	7.35
WTG04F04	7.55
WTG04F05	8.45
WTG04F06	8.05
WTG04F07	7.55
WTG04F08	8.55
WTG05F01	7.4
WTG05F02	7.3
WTG05F03	7.55
WTG05F04	7.75
WTG05F05	8.65
WTG05F06	8.25
WTG05F07	7.75
WTG05F08	8.75
WTG06F01	5.3
WTG06F02	5.2
WTG06F03	5.45
WTG06F04	5.65
WTG06F05	6.55
WTG06F06	6.25
WTG06F07	5.65
WTG06F08	6.65
WTG07F01	6.2
WTG07F02	6.1
WTG07F03	6.35
WTG07F04	6.7
WTG07F05	7.45
WTG07F06	7.15
WTG07F07	6.55
WTG07F08	7.55
WTG08F01	6.65
WTG08F02	6.55
WTG08F03	6.9
WTG08F04	7.15
WTG08F05	7.9
WTG08F06	7.6
WTG08F07	7
WTG08F08	8
WTG09F01	6.65
WTG09F02	6.55
WTG09F03	6.9
WTG09F04	7.15
WTG09F05	7.9
WTG09F06	7.6
WTG09F07	7
WTG09F08	8
WTG10F01	3.8
WTG10F02	3.7
WTG10F03	4.05
WTG10F04	4.3
WTG10F05	5.05
WTG10F06	4.75
WTG10F07	4.3
WTG10F08	5.15
WTG11F01	5.15
WTG11F02	5.05
WTG11F03	5.4
WTG11F04	5.65
WTG11F05	6.4
WTG11F06	6.1
WTG11F07	5.65
WTG11F08	6.5
WTG12F01	5.95
WTG12F02	5.85
WTG12F03	6.2
WTG12F04	6.45
WTG12F05	7.2
WTG12F06	7
WTG12F07	6.45
WTG12F08	7.4
WTG13F01	3.65
WTG13F02	3.65
WTG13F03	3.9
WTG13F04	4.3
WTG13F05	4.9
WTG13F06	4.7
WTG13F07	4.15
WTG13F08	5.1
WTG14F01	1.7
WTG14F02	1.7
WTG14F03	1.95
WTG14F04	2.5
WTG14F05	2.95
WTG14F06	2.85
WTG14F07	2.2
WTG14F08	3.15

Appendix IV. **WTG14 CRM Input Sheet**

COLLISION RISK ASSESSMENT			used in overall collision risk sheet						used in available hours sheet						
Sheet 1 - Input data			used in migrant collision risk sheet						used in large array correction sheet						
			used in single transit collision risk sheet or extended model						not used in calculation but stated for reference						
	Units	**Value**		**Data sources**											
Bird data															
Species name		**Herring Gull**													
Bird length	m	0.38													
Wingspan	m	1.44													
Flight speed	m/sec	12.8													
Nocturnal activity factor (1-5)		3													
Flight type, flapping or gliding		flapping													
				Data sources											
Bird survey data			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Daytime bird density	birds/sq km		0.17241	0.18391	0.02874	0.02874	0.14368	0.05747	0.01724	0.01724	0	0.13218	0.04023	1.50575	
Proportion at rotor height	%	28.4%													
Proportion of flights upwind	%	50.0%													
				Data sources											
Birds on migration data															
Migration passages	birds		0	0	0	0	0	0	0	0	0	0	0	0	
Width of migration corridor	km	8													
Proportion at rotor height	%	75%													
Proportion of flights upwind	%	50.0%													
	Units	**Value**		**Data sources**											
Windfarm data															
Name of windfarm site		**Theoretical**													
Latitude	degrees	52.00													
Number of turbines		202													
Width of windfarm	km	25													
Tidal offset	m	0													
	Units	**Value**		**Data sources**											
Turbine data															
Turbine model		**Gamesa G87/2000**													
No of blades		3													
Rotation speed	rpm	19													
Rotor radius	m	42.5													
Hub height	m	67	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Monthly proportion of time operational	%		86%	87%	94%	85%	92%	80%	87%	91%	92%	94%	96%	92%	
Max blade width	m	3.357													
Pitch	degrees	10													
Avoidance rates used in presenting results		95.00%		**Data sources (if applicable)**											
		98.00%													
		99.00%													
		99.50%													

Appendix V. **WTG14 CRM Overall Collision Risk Sheet**

COLLISION RISK ASSESSMENT

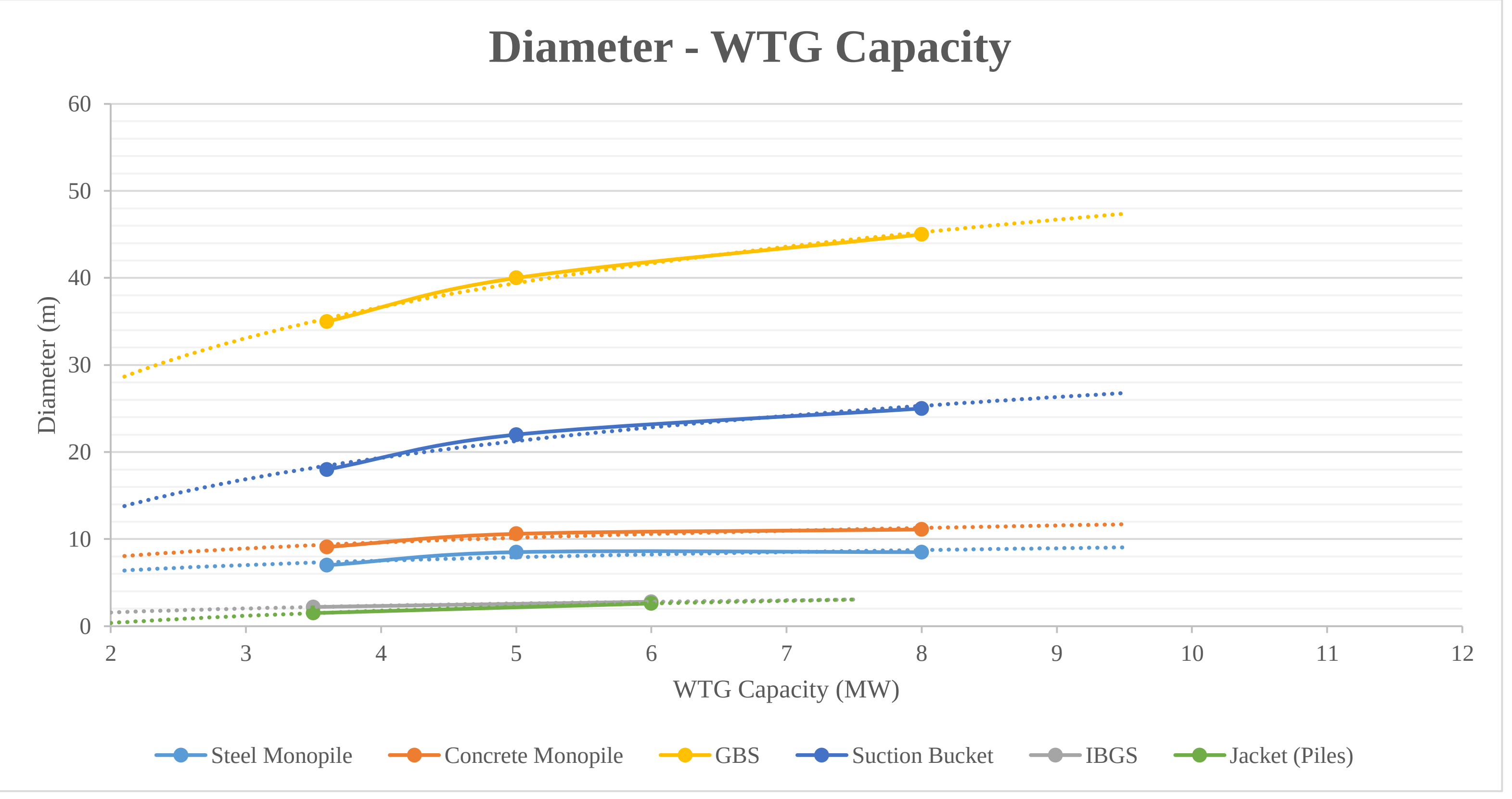
Sheet 2 - Overall collision risk

All data input on Sheet 1:
no data entry needed on this sheet!

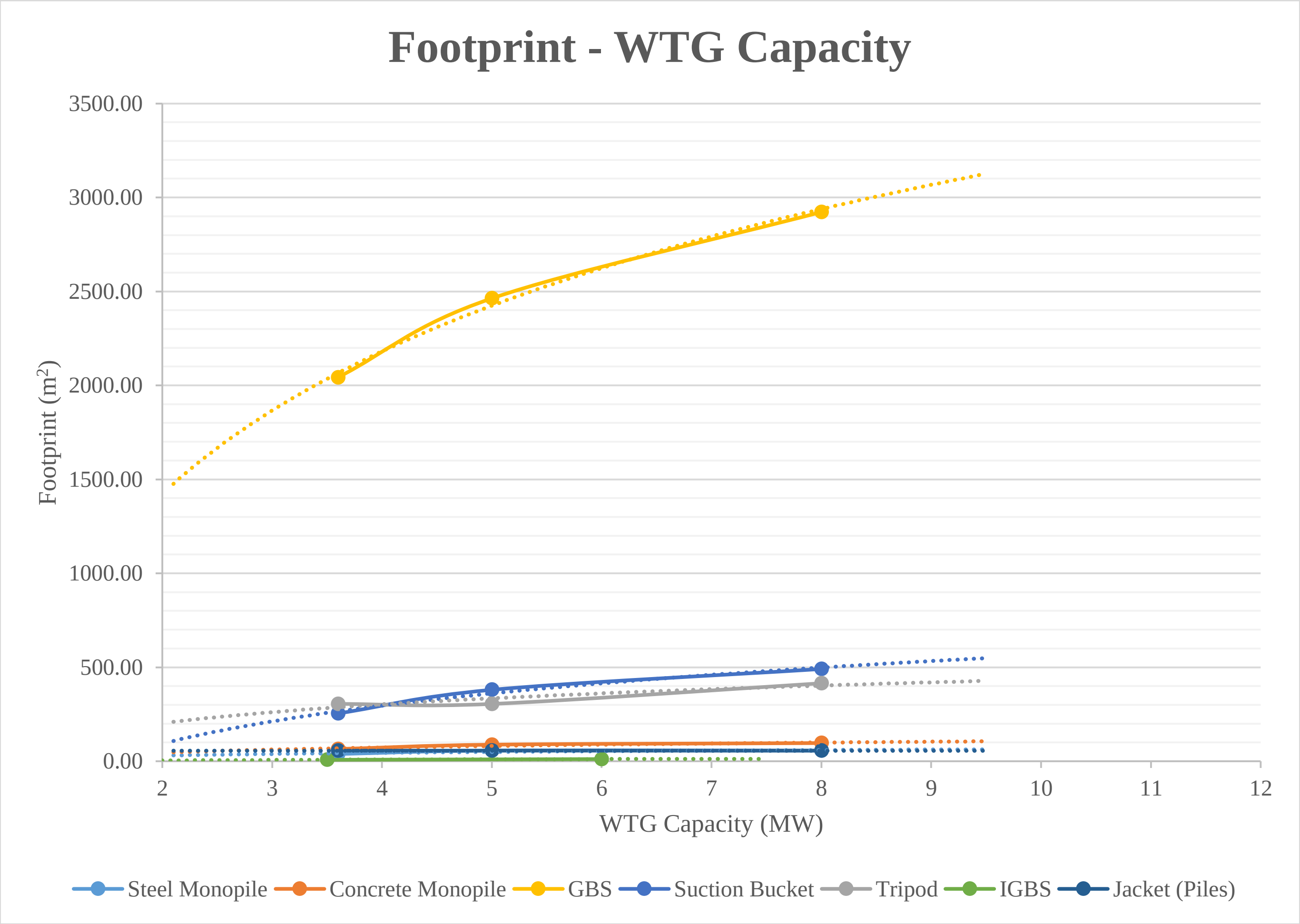
Colour key:
- from Sheet 1 - input data
- from Sheet 6 - available hours
- from Sheet 3 - single transit collision risk
- from survey data
- calculated field

Bird details:															
Species		Herring Gull													
Flight speed	m/sec	12.8													
Nocturnal activity factor (1-5)		3													
Nocturnal activity (% of daytime)		50%													
Windfarm data:															
Latitude	degrees	52.0													
Number of turbines		202													
Rotor radius	m	42.5													
Minimum height of rotor	m	67													
Total rotor frontal area	sq m	1146249													
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**year average**
Proportion of time operational	%		86%	87%	94%	85%	92%	80%	87%	91%	92%	94%	96%	92%	89.6%
Stage A - flight activity															
Daytime areal bird density	birds/sq km		0.17241	0.18391	0.0287	0.0287	0.143678	0.057471	0.017241	0.017241	0	0.132184	0.04023	1.505747	
Proportion at rotor height	%	28.4%													
Total daylight hours per month	hrs		258	277	367	416	485	499	503	455	382	332	266	243	
Total night hours per month	hrs		486	395	377	304	259	221	241	289	338	412	454	501	
Flux factor			53684	54222	9917	10140	54870	21769	6679	6421	0	44187	12329	461885	
Option 1 -Basic model - Stages B, C and D															**per annum**
Potential bird transits through rotors			15246	15399	2816	2880	15583	6182	1897	1824	0	12549	3501	131175	**209053**
Collision risk for single rotor transit	(from sheet 3)	8.5%													
Collisions for entire windfarm, allowing for non-op time, assuming no avoidance	birds per month or year		**1108**	**1130**	**225**	**208**	**1215**	**419**	**140**	**141**	**0**	**995**	**284**	**10216**	**16081**
Option 2-Basic model using proportion from flight distribution			**235**	**240**	**48**	**44**	**258**	**89**	**30**	**30**	**0**	**211**	**60**	**2169**	**3414**
Option 3-Extended model using flight height distribution		Herring Gull													
Proportion at rotor height	(from sheet 4)	6.0%													
Potential bird transits through rotors	Flux integral	0.0318	1707	1725	315	323	1745	692	212	204	0	1405	392	14691	**23413**
Collisions assuming no avoidance	Collision integral	#¡VALOR!	#######	#######	######	######	########	########	########	########	########	########	########	########	**#¡VALOR!**
Average collision risk for single rotor transit		#¡VALOR!													
Stage E - applying avoidance rates															
Using which of above options?	**Option 2**	0.00%	235	240	48	44	258	89	30	30	0	211	60	2169	**3414**
Collisions assuming avoidance rate	birds per month or year	95.00%	12	12	2	2	13	4	1	1	0	11	3	108	**171**
		98.00%	5	5	1	1	5	2	1	1	0	4	1	43	**68**
		99.00%	2	2	0	0	3	1	0	0	0	2	1	22	**34**
		99.50%	1	1	0	0	1	0	0	0	0	1	0	11	**17**
Collisions after applying large array correction		95.00%	12	12	2	2	13	4	1	1	0	11	3	108	**171**
		98.00%	5	5	1	1	5	2	1	1	0	4	1	43	**68**
		99.00%	2	2	0	0	3	1	0	0	0	2	1	22	**34**
		99.50%	1	1	0	0	1	0	0	0	0	1	0	11	**17**

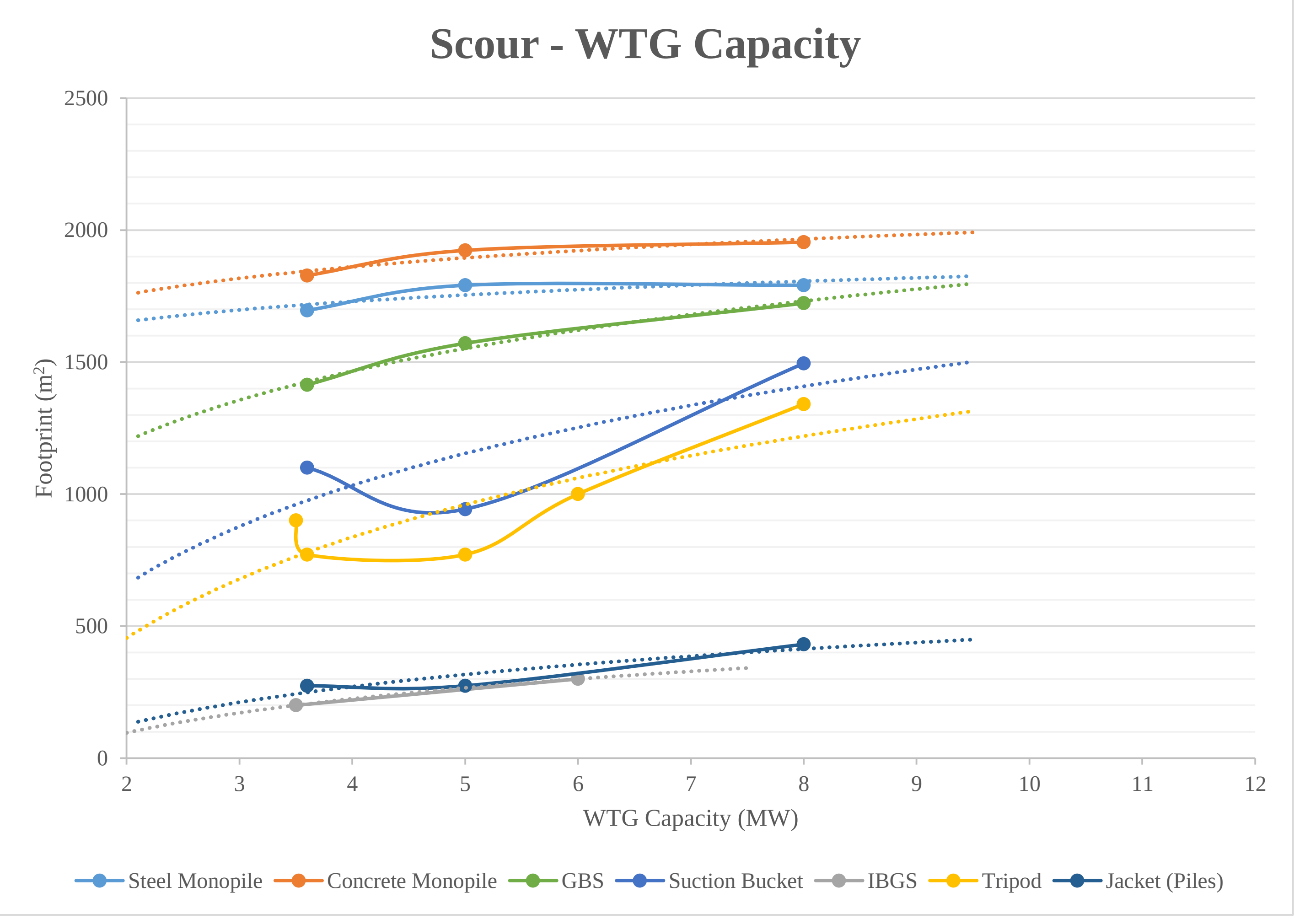
Appendix VI. **Diameter - WTG Capacity Regression**



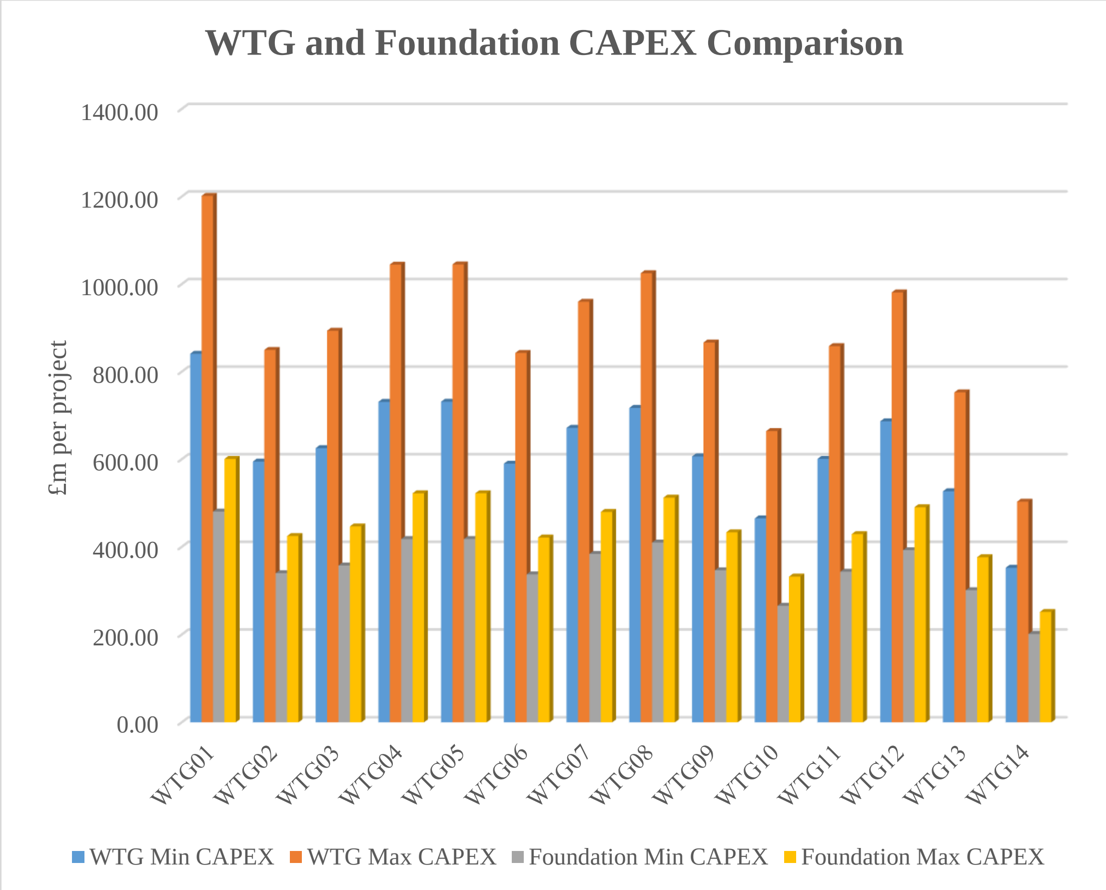
Appendix VII. **Footprint – WTG Capacity Regression**



Appendix VIII. **Scour Protection – WTG Capacity Regression**



Appendix IX. LCoE CAPEX Comparison



	WTG		Foundation	
	Min % CAPEX	Max % CAPEX	Min % CAPEX	Max % CAPEX
WTG01	841.14	1201.63	480.65	600.82
WTG02	594.90	849.85	339.94	424.93
WTG03	625.55	893.64	357.46	446.82
WTG04	731.30	1044.71	417.88	522.35
WTG05	731.61	1045.15	418.06	522.58
WTG06	590.10	843.00	337.20	421.50
WTG07	671.95	959.93	383.97	479.97
WTG08	717.51	1025.01	410.00	512.51
WTG09	606.69	866.70	346.68	433.35
WTG10	465.19	664.55	265.82	332.28
WTG11	601.01	858.59	343.44	429.29
WTG12	686.83	981.19	392.48	490.60
WTG13	527.10	753.01	301.20	376.50
WTG14	352.35	503.35	201.34	251.68