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Assessment of cumulative impacts in offshore wind developments

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Signed: K.Shearer   Date: 19th September 2013

Abstract

Offshore wind has become the technology of choice in order for the UK government to reach their carbon emission reduction targets by 2020. By use of Environmental impact assessment (EIA) techniques, potential impacts are assessed and mitigation options explored. Many EIA's use the "Rochdale Envelope" to determine the parameters in which the project will fall, therefore mitigating against any possible impact in a wide range of constraints. This was particularly useful in Round 1 and 2 of the Crown Estate release of the seabed as there were many unknowns particularly about the construction and operational phases of the projects and therefore the ability to have a wide range of parameters was an advantage. However for Round 3 projects this is creating issues in terms of maximum potential impacts exceeding the limitations allowed in EU directives when projects are considered in combination; the cumulative impact is too large using the "worst case scenario". This is putting potential projects in danger of being denied planning permission as they will be too detrimental to the environment.

Key objectives were to model the environmental impact of different base structures and rated capacities of turbines in cumulative scenarios as technology is likely to change over the course of the future. The relationship between installation methods and mitigation techniques were examined for both scour and noise, and an economic study is carried out.

Using the Environmental Evaluation System (EES) it is realised that as technology progresses, fewer turbines are installed to reach the developments rated capacity. The cumulative impacts of installation operation and decommissioning are therefore reduced and the "worst case" as defined in the Rochdale Envelope will be more defined, allowing more projects to be commissioned.

Fewer turbines will also lead to less intrusive installation periods, and less scour, both of which are detrimental to the surrounding environment. However base structures, turbines and installation techniques are not only guided by environmental constraints, but also engineering and economic factors have to be taken into consideration.

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Contents

Abbreviations

ADD	Acoustic Deterrent Device
BEP	Basic Environmental Parameters
dB	Decibel
CEA	Cumulative Effects Assessment
CCW	Countryside Council for Wales
COWRIE	Collaborative Offshore Wind Research Into the Environment
DCO	Development Consent Order
DECC	Department of Energy and Climate Change
EC	European Community
EES	Environmental Evaluation System
EIA	Environmental Impact Assessment
ERA	Environmental Risk Assessment
ES	Environmental Statement
EU	European Union
EQ	Environmental Quality
EQU	Environmental Quality Units
GBS	Gravity Base Structures
GEC	General Environmental Categories
GW	Gigawatt
HSD	Hydro Sound Damper
IEC	Intermediate Environmental Components
JNCC	Joint Nature Conservation Council
KC	Keulegan-Carpenter number
LCA	Life Cycle Assessment

MW	Megawatt
NE	Natural England
NEPA	National Environmental Policy Act
OWF	Offshore Windfarm
PIU	Parameter Importance Units
PTS	Permanent Threshold Shift
SEA	Strategic Environmental Assessment
TCE	The Crown Estate
TTS	Temporary Threshold Shift
UK	United Kingdom

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1. Introduction

1.1 Background

The current energy policy for the UK builds upon the EU-wide drive to reduce carbon dioxide and greenhouse gas emissions in order to tackle climate change. There is a need to replace existing infrastructure as around 25% of the UK electricity generating capacity will be lost through scheduled power station closures by 2018 (HM Government, 2009). Renewable energy will provide a greater security of supply as without abundant fossil fuels readily available in the UK, at the moment it is already a net importer of gas and coal to fuel power stations. Overall fossil fuel demand in the UK is forecast to be reduced by 10% and gas imports are to be reduced by 20-30% compared to what they would have been in 2020 if the UK was following its current trajectory of building sustainable renewable developments. This is also due to a commitment to reducing emissions of carbon dioxide by over 750 million tonnes between now and 2030 (HM Government, 2009).

The UK government has committed to sourcing 15% of its energy, including 30% of its electricity from renewable sources by 2020 (DECC, 2009). Of this percentage, offshore wind is expected to make the single biggest contribution as the UK has the largest offshore wind resource in the world and 33% of Europe's potential offshore wind resource (Scottish Executive, 2008), combined with relatively shallow waters and strong winds (DECC, 2010). Other advantages of offshore wind is that it tends to flow at higher speeds, and with more consistency than on land, therefore turbines produce more electricity as the potential energy produced from the wind is directly proportional to the cube of the wind speed and increased wind speed of only a few miles an hour can produce a significantly larger amount of electricity (DECC, 2010). Due to economies of scale, offshore turbines are also larger than their onshore counterparts.

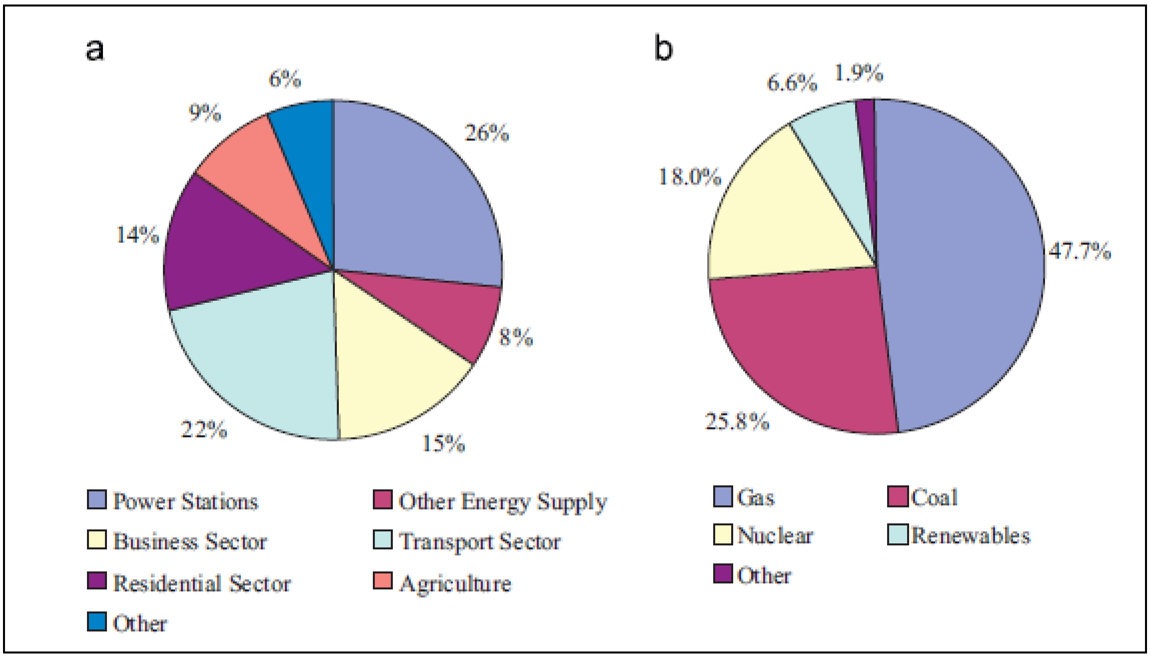

Figure 1: (a) and (b)The UK Greenhouse Gas emissions by sector in MtCO2e (2009) and the UK electricity mix (2009–2010) by energy source (DECC, 2010).

There are several options for assessing the potential cumulative impact of offshore wind farms on the environment. Traditionally individual project assessments are based on 'worst-case' assumptions under the Rochdale Envelope principle, and these are added up to assess the cumulative impact. However, it is apparent that the cumulative 'worst-case' is not a 'realistic' scenario. This approach has the potential to result in individual projects potentially being refused consent e.g. Sandwich terns in The Wash. Developers are concerned that this principle will become more prevalent in the consenting of Round 3 projects and are therefore seeking ways to reduce the over-precautionary cumulative assumptions built into most assessments. There is an urgent need to better understand how to assess cumulative impacts based on realistic scenarios.

One of the first steps in this process is being able to make informed decisions on the potential implications of different development scenarios on environmental receptors. There are many different development scenarios possible to reach a target generation capacity based on turbine design (MW), foundation design, array layout etc. An example of the inter-relationship between one such aspect is detailed below:

Gravity-base foundation vs. Mono-pile foundation: Gravity bases have a larger physical impact footprint and therefore greater potential impacts on benthic communities (habitat loss, invasive species etc) but installation methods result in lower noise emissions and potential impact on marine mammals.

It is obvious there is a trade-off between environmental impacts (consentability) and engineering/cost considerations (constructability) that have to be considered. There is a requirement to standardise the process by which these are considered during strategic planning and decision making process thus providing an audit trail.

This paper seeks to find a technique to assess the potential cumulative impacts during the early stages of the planning process, using present and future turbines and different foundation types. Two major cumulative impacts which were recognised through the evaluation technique used are examined in-depth to determine scale of effect and to appraise current mitigation techniques.

1.2 Environmental Impact Assessment

An Environmental Impact Assessment (EIA) is a systematic process which is undertaken during the planning stages of a major development project to determine what effects, if any, the project will exert on the environment, and what will be done to control any adverse outcomes if they are deemed above acceptable limits (Jay et al., 2007). From an EIA an Environmental Statement (ES) is published so that the potential environmental effects can be effectively communicated to decision-makers and the broader public. It can be a useful tool for collecting data on a project design or for citing a project in a particular area.

EIA was developed as part of the National Environmental Policy Act 1969 (NEPA) in the United States (Wood, 1995). The basis of the EIA has UK the EIA was introduced in 1988 following the approval of Directive 85/337/EEC in 1985 (Barker et al., 1999). In the EU the EIA process is in the form of a framework law, which is an outline of the overall principles, objectives and guidelines but allows a certain amount of discretion in the realisation of the directive (Lee, 1995). This freedom leads to a variation of effectiveness across the EU as understanding and monitoring of the implementation of the process is undertaken at member state level; however this also allows a degree of flexibility of the data presented to the planning inspectorate.

The scoping process (Figure 2) is designed to define the topics for inclusion as part of an EIA and outlines the methodologies for surveys to assess significance criteria against which risks and potential impacts can be identified. It also allows determination of 'proportionality' to data collection and any issues to be removed that are not considered to be significantly affected by the project. An important part of the scoping process is the ability to make an initial prediction of impact from both direct and indirect effects and establish understanding about the component parts of the proposed development. Spatial extent, magnitude, timing, frequency and duration which defined the parameters as described by the Rochdale Envelope and what data will be required to characterise the environment within the zone of impact (Cefas, 2012) after existing information on the 'natural environment' has been measured and collated to identify critical gaps.

Impact significance determination is widely recognised as a vital and critical EIA activity (Lawrence, 2007). Although generally acknowledged as pivotal to EIA practice, impact significance determination remains one of the most complex and least understood of EIA activities (Wood et al., 2004).

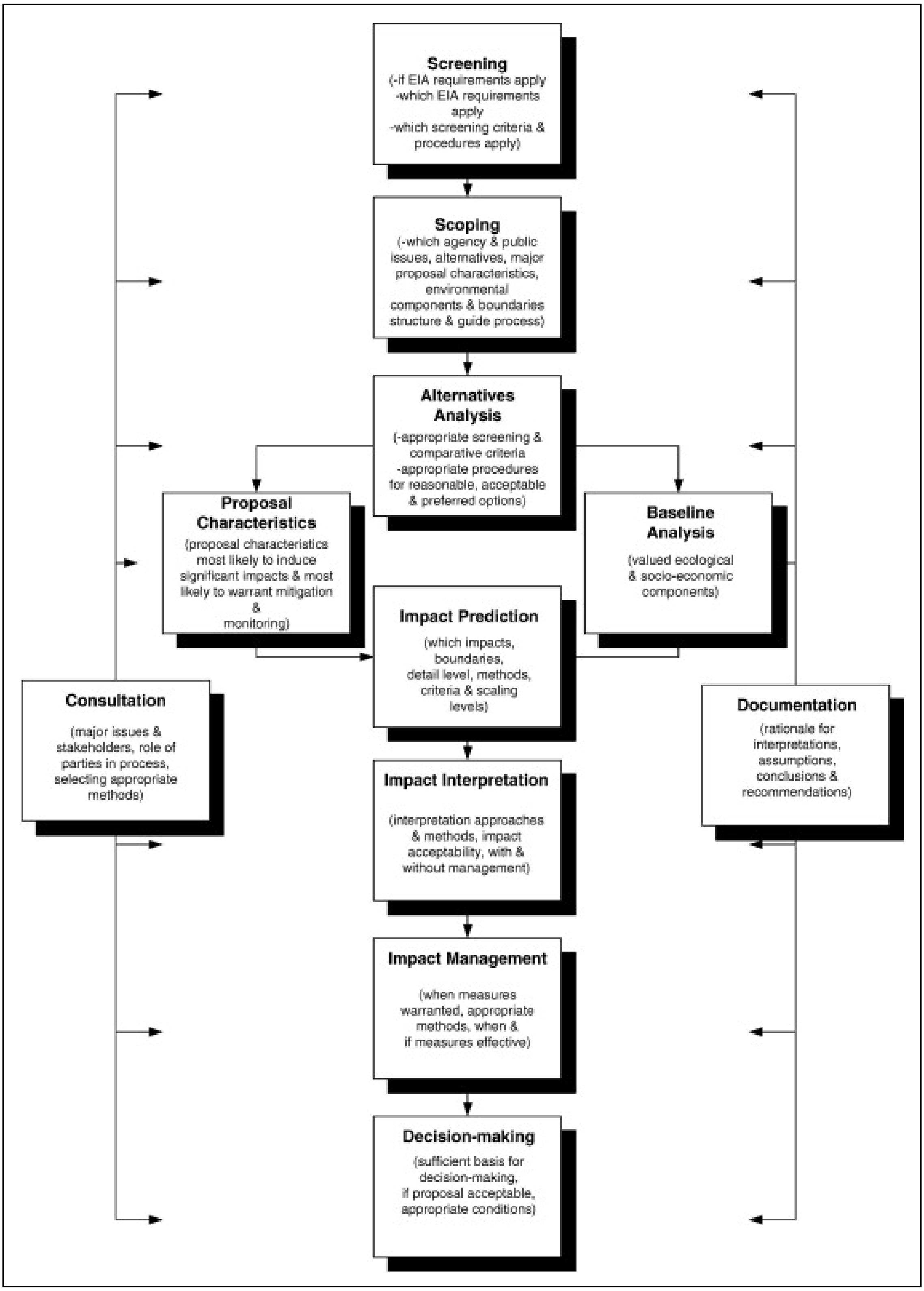

Figure 2: Impact significance interpretations in the EIA process (Lawrence, 2007).

Environmental Risk Assessment (ERA) is a qualitative and quantitative valuation of environmental status, and is comprised of both human health risk assessment and ecological risk assessment. Human health risk assessment includes hazard identification, dose-response assessment, and exposure assessment and risk characterization. Ecological risk assessment is used to determine the likelihood of the occurrence of adverse ecological effects as a result of exposure to stressors.

There are huge uncertainties on environmental assessments due to the lack of understanding of cause-effect relationships in the natural environment which is highly complex, and lack of scientific theory on the subject (Galatchi, 2005). Models used in order to quantify the case-effect relationships may not correspond with reality; this may be due to weaknesses in the available data, including data gaps and poorly researched areas. In the case of some data, it is extrapolated from a small experimental group to suit larger groups of receptors; however larger groups may not correspond in the same way as there is a natural variation on environmental parameters for each group of receptors dependent on size, type and locality. If assumptions are made, these are also open to their own levels of sensitivity, dependent upon which data the assumptions were based.

1.3 Offshore Developments

The Crown Estate (TCE) owns almost the entirety of the seabed to 12 nautical miles, and therefore has an obligation to manage this asset on behalf of the Crown under the Crown Estate Act 1961. As TCE is a government body, it works closely with the treasury, following Government Policy to dictate its operation. They reserve the right to generate electricity from wind, waves and tides on the continental shelf under the Energy Act 2004 (Crown Estate, 2013). Offshore wind plays a significant role in the energy portfolio which is focused on renewable energy. Since 2000 there have been five rounds of offshore wind which have increased in scale and technical complexity as the industry matures (Round 1, 2, 3 and extensions to Round 1 sites and additional sites in Scottish Territorial Coastal Waters), each round identifies areas of the sea bed which would be most appropriate for development with minimal disturbance to the environment but with maximum power output. These areas are subsequently made available for renewable energy developers to bid for exclusive rights to lease these areas in order to construct windfarms to generate electricity within these zones.

The UK Offshore Energy Strategic Environmental Assessment (SEA) (DECC, 2009), identified up to 33GW of offshore wind capacity in UK waters which formed the basis of the most recent Round 3 offshore wind programme where nine offshore wind farm zones of varying sizes were identified.

Although TCE has identified zones for development, the areas still have to undergo consent for planning which will be applied for by each developer. It is during this stage that an EIA should be undertaken to scope, investigate possible impacts and propose mitigation techniques for each area that is sought for development.

As each round has been released, knowledge about how best to develop within each zone has evolved. During Round 1 consultation, developers had to obtain three separate licences for navigation, coastal protection and for an electricity power plant, however for Round 3 the process has changed so that consent for all three are obtained at the same time (Toke, 2011). Due to the amount of unknowns in offshore development, leases for Round 1 were very prescriptive as to where developments could be located, however developers are given more of a margin of negotiation with other stakeholders and interested parties to select positioning of turbines in Round 3 sites in a bid to minimise clashes.

It is important to distinguish between “impact” and “effect” and the two have distinct meanings. In essence, an effect is a response to an action and an impact is the final outcome due to an effect. A direct impact on bird population would be birds colliding with the turbine structures themselves, however effects can be indirect resulting in an impact; habitat use can be affected during wind farm construction and operation, resulting in birds avoiding the immediate vicinity of the area, therefore feeding habits change, resulting in effective habitat loss (Fox et al., 2006).

There are also many impacts that can have both positive and negative effects, and quantifying which is the best course of action to take can be difficult. Restricting fishing can be something of a double edged sword, British fishing interest groups may mount legal challenges to any incursions placed on Natura 2000 sites, however although wildlife conservation groups may sympathise with farmers regards disruption to their fishing routes and potential loss of trade, it may be that it is in the interest of conservationists that the restriction of fishing through allocation of windfarm sites may be of benefit to their interests; fishing resources may be conserved and ecological protection could be provided for threatened species (Toke, 2011).

1.4 Rochdale Envelope

Traditionally individual project assessments for offshore windfarms are based on 'worst-case' assumptions under the Rochdale Envelope principle, and these are added up to assess the cumulative impact.

The Rochdale Envelope is a well established approach to planning consent, it was devised after two cases were brought to court over planning applications for a proposed business park in Rochdale: 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] (The Planning Inspectorate, 2011) that sought to address applications for planning permission under the Town and Country Planning act 1990, and consideration of an EIA in the context of an outline planning consent to enable compliance with the Council Directive 85/337/EEC as transposed by the Town and Country Planning (EIA) (England and Wales) Regulations 1988. The implications arising from this case had a significant effect on future planning applications for large scale developments.

Projects were to have clear, defined parameters, with emphasis put on the amount of detail the proposal should contain; the larger the amount of information given would mean it would be easier to ensure that regulations would be adhered to whilst allowing a proper assessment of the likely environmental effects and outline of the necessary possible mitigation steps:

> "*The assessment may conclude that a particular effect may fall within a fairly wide range. In assessing the 'likely' effects, it is entirely consistent with the objectives of the Directive to adopt a cautious 'worst case' approach. Such an approach will then feed through into the mitigation measures envisaged.... It is important that these should be adequate to deal with the worst case, in order to optimise the effects of the development on the environment*" (para.122 of the Judgment, in The Planning Inspectorate 2011).

The 'Rochdale Envelope' has since been held by developers as a useful approach when considering applications for a Development Consent Order (DCO), where details of the impacts and mitigation techniques for the whole project are not yet known when the application deadline is due. This approach has also been used under other regimes such as the Town and Country Planning Act 1990 and the Electricity Act 1989.

The Department of Energy and Climate Change (DECC) (2011) has applied this approach to the UK's Overarching National Policy Statement on Energy:

"In some instances it may not be possible at the time of the application for development consent for all aspects of the proposal to have been settled in precise detail… the [Environmental Impact Assessment (EIA)] should set out, to the best of the applicant's knowledge, what the maximum extent of the proposed development may be… and assess, on that basis, the effects which the project could have to ensure that the impacts of the project as it may be constructed have been properly assessed."

For Round 1 and 2 projects, the Rochdale Envelope allowed developers to propose developments within a wide range of parameters; this provided an opportunity to change the design of the development at late stages of the process, mainly brought about by advances in technology and more efficient methods of installation. It also allowed developers a degree of movement regarding adverse consequences of the developments, and planning for extreme thresholds should they occur in the relatively infant stages of developing renewable energy wind farms offshore.

However, it is apparent now that Round 3 stages are entering the planning phase that the cumulative 'worst-case' scenario as represented by the Rochdale Envelope is not a 'realistic' scenario as it is very rarely the case that environmental effects that take place during the construction and operational phases of a development reach their upper boundaries as outlined in the ES. This approach has the potential to result in individual projects potentially being refused consent as on paper it looks like projects would be breaching environmental constraints, which could be detrimental to the progress to the development of offshore wind farms.

1.5 Cumulative Impacts

Three interested parties put in planning applications for offshore wind developments in the Greater Wash area of the North Sea on the East Coast of England (Figure 3), Warwick Energy applied for 560MW Dudgeon wind farm and Centrica applied for two; 580MW Race Bank and 540MW Docking Shoal project. Both the Dudgeon wind farm and the Race Bank windfarms were approved, however the site at Docking Shoal was rejected on the grounds of too many birds, mainly Sandwich Terns would be killed by turbine blades in combination with the other two projects.

The rejection was due to the size of the Rochdale Envelope on each windfarm; using the "worst-case" scenario showed that in combination, all 3 developments would be detrimental to the population of Sandwich Terns if they were all in operation simultaneously (Centrica, 2009).

It is generally accepted that fewer turbines cause less collisions, however as the projects had to model each configuration under consideration, the worst case scenario with many turbines showed that there would be a statistically significant decline in populations. This population modelling and risk based approach was detrimental to the planning process of Docking Shoal based on the cumulative impact assessment, however this only became apparent during the later stages of the project planning process. In order to save time and money, a quick method of assessment needs to be used to gauge where the weaker areas of the project are likely to occur.

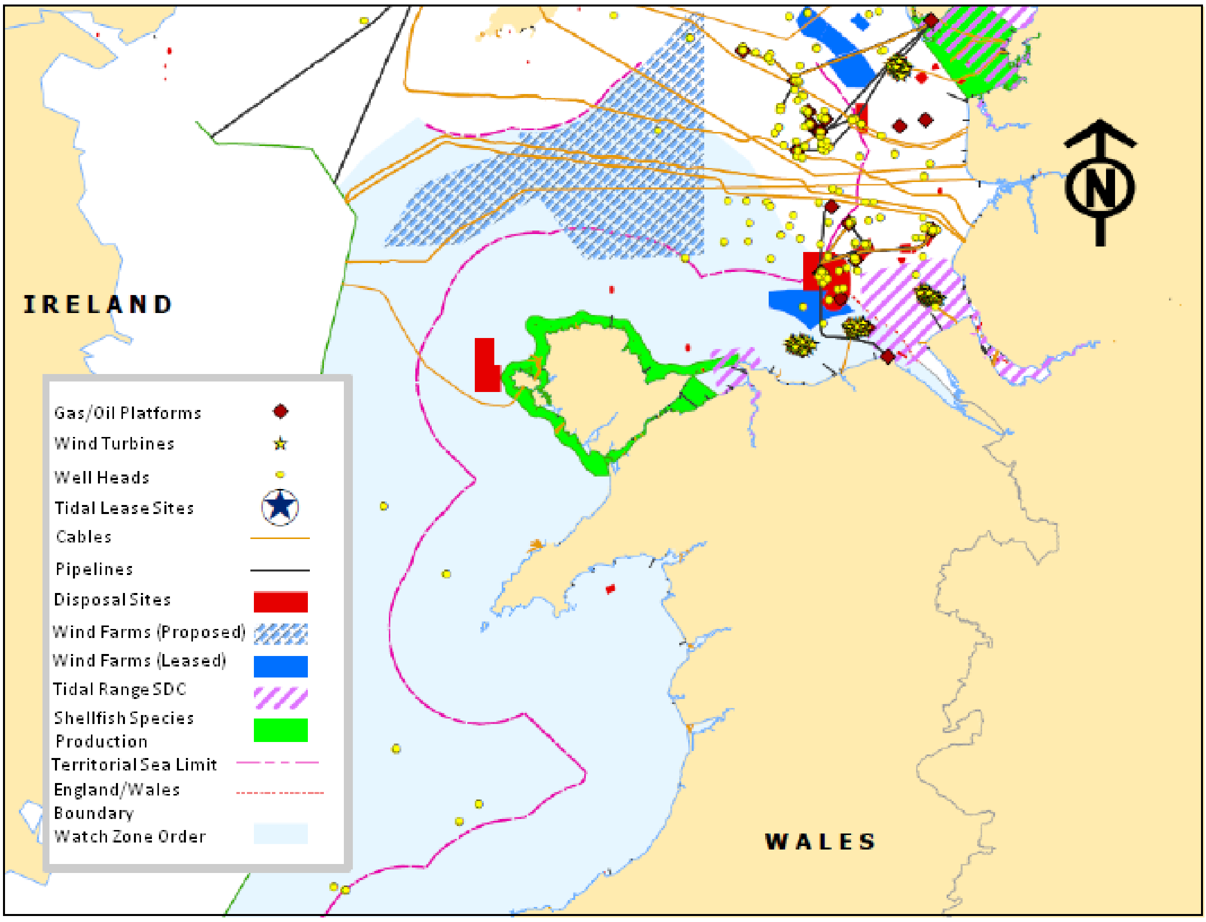

Figure 3: Multiple users in coastal waters through the proposed site for Shell Flats windfarm (JNCC 2000)

Cumulative effect prediction both identifies intra project effects and the effects of the plans in combination with those of other activities in the area (Thrivel et al., 2007). It is an indication of how a given receptor is affected by plans and can be used on projects of different scales. Prediction is difficult due to the complex interaction between all the variables involved (Figure 4), and effect is difficult to quantify for many things; for birds the migration path is affected once for some species but many are affected due to loss of breeding ground.

The real issues that arise within the Rochdale Envelope when projects are to be placed nearby other developments that are either in the process of planning, development or commissioning. With the case of the Sandwich Terns at the Wash it was felt in combination with the neighbouring projects, it would provide a significant barrier for the birds who feed within the marine environment, too many collisions were to occur if all the projects were fully developed with the parameters defined during the planning process.

Although this project steers away from pinpointing specific species, it is however useful to gain a broad idea of what would be affected given neighbouring developments, and at what stage the Rochdale Envelope is breeched.

For the installation phase, the main concern is with the noise, particularly if monopiles are the main type of foundation to be used, therefore within a single development, distance between the turbines determines installation time so as not to create too much noise. The planning processes taking place are also staggered so that developers do not compete with the Planning Authority for planning permission at the same time; therefore it is highly improbable that another array can be at the same stage of development; however neighbouring projects have to be considered within the environmental statement. Therefore for considering accumulation effects of parameters within the Rochdale Envelope for neighbouring arrays, only the operational stage is considered. At a more strategic level Cumulative Effects Assessments (CEA) are used to determine the siting, phasing and managing of projects so that any adverse effect can be mitigated or avoided before a large scale issue occurs (Thrivel et al., 2007). In the UK CEA-related mitigation has come about as a response to the European Commission Habitat Directive (1992). The main effect the implementation of the directive had was the introduction of Natura 2000 network of sites, which requires an "appropriate assessment" for any project in combination with other projects that are likely to have a significant effect on local habitats (Thrivel et al., 2007). In 2000 the European Commission specified that cumulative effects have to be measured over time so that underlying effects can be analysed. It has to be proven that a project will not adversely affect the integrity of the site or else the project will be rejected and alternative solutions will have to be sought.

Developers are concerned that this principle will become more prevalent in the consenting of Round 3 projects and are therefore seeking ways to reduce the over-precautionary cumulative assumptions built into most assessments. There is an urgent need to better understand how to assess cumulative impacts based on realistic scenarios.

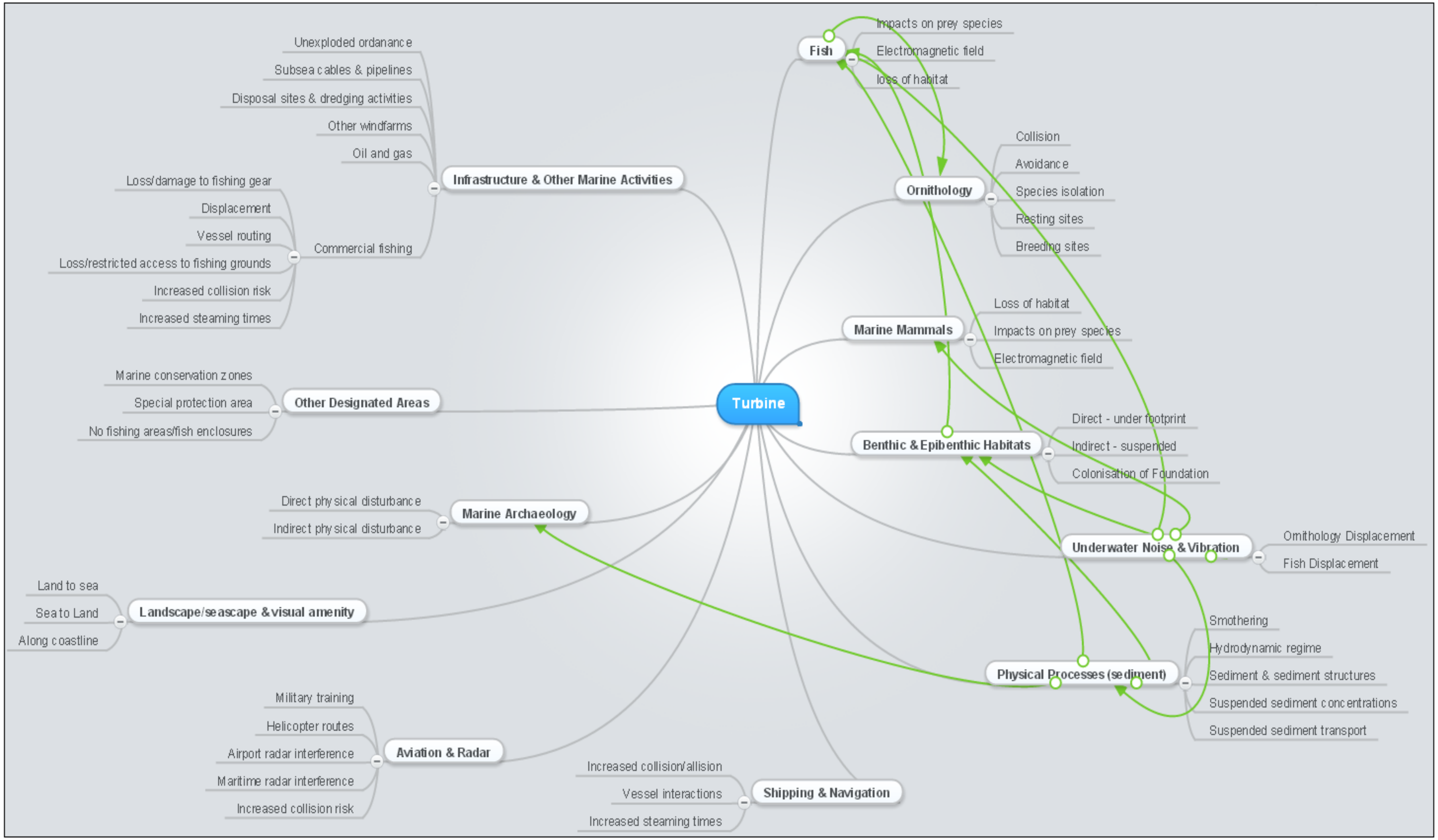

Figure 4: Complex interaction between variables in offshore windfarm developments

1.6 Onshore Windfarms

Offshore windfarms are essentially a marinised version of their onshore counterparts so to it would be a reasonable assumption that the onshore EIA process would apply directly to offshore developments. However where cumulative impacts are concerned this is not quite the case.

Investigations into the cumulative impacts of onshore windfarms mainly concern public attitudes towards the number of turbines (Anderson et al., 2008, Landenburg et al., 2012) rather than the cumulative impacts that would affect the environmental baseline prior to the development.

Cooper et al., (2002) sampled 50 UK ES's for onshore wind developments, only 48% of these mentioned “cumulative impacts” and only 18% provided a discussion of the lasting effects, which were mostly qualitative, focusing on public perception of wind turbines, only 1 diverted the attention away from perceived negative impacts to highlighting improved air quality through increased numbers of wind turbine development in the local area compared with a coal fired power station that was proposed some years before. The aim of the European Community (EC EIA Amendment Directive 97/11/EC) and UK Regulations sought to strengthen the relationship between projects and cumulative impacts during the scoping process; however this was not mandatory for either authorities or developers to carry out this stage of the process. To date, little attention has been given to proposed developments and their interaction with other existing or proposed developments and their cumulative effects (Jones et al., 2011).

The EIA process for offshore windfarms has taken a more holistic approach, where a more comprehensive impact assessment has been undertaken of cumulative impacts.

European legislation requires a Strategic Environmental Assessment (SEA) of national Offshore Windfarm (OWF) programmes and EIA’s for individual projects likely to affect birds to identify areas of sensitivity such as those used for breeding or feeding (Fox et al., 2006).

1.7 Oil and Gas

When investigating the potential environmental disturbances from construction of offshore wind farms, it may be sensible to reference the similarities that might occur between oil and gas exploration as there are several similarities that can be drawn between the infrastructure and construction phases. In the 1970's when oil and gas was first being explored in the North Sea, the idea of conducting an EIA was just that, as there was no similar process in the UK to the EIA process adopted in the United States. Conducting an EIA in the UK was proposed by consultants who wanted to know what effect oil developments would have on Scottish coastal villages (Bichard et al., 1988), however developing a suitable strategy took several years and by 1985 the European Directive was established. It was recommended that the EIA be integrated into the existing planning system and co-ordinated by strategic planning authorities, requiring developers to make an assessment of the impacts of their development proposal and suitable mitigation methods described in order to minimise the impact.

Without the need to justify any environmental impacts and possible mitigation techniques, oil platforms and subsea pipes were installed rapidly, often without the potential reserve volume being known (Lyddon. 1983) between 1970 and 1975, 15 commercially viable fields had been discovered, and all the main terminals, bases and construction yards were secured as well as 4 undersea pipelines needed to transport oil to the mainland (Lyddon 1983). Locals affected by this sudden change in lifestyle – jobs paying a high wage, large infrastructure built close to dwellings, many visitors to the area – were astounded that neither developers nor the government could predict how long this "oil boom" would last for as there was no reasonable method by which to predict the volume of the oil reserves or how long the exploration would last, and therefore were wary of the effects the developments would have on their livelihood including traditional means of making money from the land and sea.

However nowadays, the process is much more stringent with advice being sought from DECC about the direction an EIA should take as well as the inclusion of potential mitigation measures and public consultations. This is to ensure thet all of the potential impacts arising from the project are considered and that stakeholders are given the opportunity to raise any issues during the consultation period.

An advantage that offshore wind turbines have over oil and gas infrastructures is that the risk of spillage or leakage of hydrocarbons is greatly reduced during the operational phase (Fraser et al., 2011).

2. Turbines

2.1 Background

The average capacity rating of the offshore wind turbines installed in 2012 was 4MW, 11% bigger than in 2011. It is expected that the average wind turbine size will not increase significantly over the next 2 years (EWEA, 2013). Although the next generation turbines with larger capacities and rotor sizes improve the business case, the Offshore Operations Department at Iberdrola hold an element of doubt that the product development plans announced by some suppliers will be able to deliver the large milestones that have been announced (Personal Communication, Iberdrola Personnel); many face manufacturing and supply chain challenges that have no foreseeable solution such as the security of rare earth materials for the permanent magnet generators as well as the non realisation to date of a reduction in costs and improvement in performance (Iberdrola, 2013). Despite these challenges, 38 new offshore turbine models have been announced by 31 companies, 52% of which are from European companies. Three quarters of these announcements are for turbines rates at or above 5MW (EWEA, 2013)

Five turbines were chosen for this study, ranging from the commonly used to those that are still in the ages of development. This allows a broad range of parameters to be utilised on the effect of turbine size and environmental impact.

2.1.1 Vestas V112-3.0MW

This model is available for on and offshore sites, it is ideal for high winds with low turbulence, it already has an onshore installed capacity of 1.5GW with a further 1.5GW awaiting installation. Vestas is the second largest offshore wind turbine generator supplier in Europe with 28% of total installed capacity (EWEA, 2012), and 89 Vestas V112's are to be installed at the E.ON development in the Humber Gateway, 72 for the Norwind Project and

Vattenfall are planning to use 17 for the proposed extension at the Kentish Flats development.

2.1.2 Siemens SWT-3.6-120

Described as the "workhorse" of the Siemens portfolio (Siemens, 2013); in 2011 there was an installed capacity of 1,714MW and a further 3,467MW planned for 2012/2013, of which 2,808MW is planned to be installed offshore across Europe (Iberdrola, 2013). The gears are helical to minimize noise. These turbines are currently installed in many of the UK offshore sites including; Burbo Bank, Greater Gabbard, Gunfleet Sands, Rhyl Flats and Sheringham Shoal.

2.1.3 Areva M5000-135 5MW

Areva's flagship turbine design for offshore utility; it is based upon the successful M5000-116 onshore turbine technology with a strengthened hub and yaw bearing. The blade design was a compromise between load, structure, production and aerodynamic advantages to be safe and strong for use offshore. There are 100 turbines planned for Saint-Brieuc, France, as part of a development by RES and Iberdrola, and 80 planned for the Wikinger site in the Baltic Sea, also to be developed by Iberdrola.

2.1.4 Repower 6M

Developed after the success of older models 3M and 5M, the 6M is constructed to cope with power flux and tough environmental conditions. Elastic bearings in the drivetrain allow for sound and vibration decoupling from the main frame. Thirty installations are planned for the RWE development at Thorntonbank II off the Belgian coast.

2.1.5 Vestas V164-8.0MW

The V164 platform was successfully utilised on the V164 7MW, was developed with the intention of increasing turbine size (Vestas, 2012), in its infancy, this 8MW model has a large rotor diameter of 164m, with the vision of reducing turbines to get maximum yield from wind power, whilst also reducing the need for foundations, lowering the environmental impact. This turbine is expected to reach the testing stages in early 2014 (Vestas, 2013).

N.B. Data for this turbine including maximum water depth and foundation diameters are yet unknown and therefore is extrapolated from the information from other turbines.

Technical Data	Vestas V112-3.0MW	Siemens SWT-3.6-120	AREVA M5000-135 5MW	REpower 6M	Vestas V164-8.0MW
Power (MW)	3	3.6	5	6.15	8
No of blades	3	3	3	3	3
Rotor Diameter (m)	112	120	135	126	164
Rotor Swept Area (m2)	9,852	11310	14,314	12,469	21,124
Rotor speed range (RPM)	8.1-17.7	5.0-13	6.6-15.1	7.7-12.1	4.8-12.1
Cut-in Wind speed (m/s)	3	4	3.5	3.5	4
Cut-out wind speed (m/s)	12	25	25	30	25
Nominal power at (m/s)	11.3	12.5	11.4	14	11
Hub height (m)	75	90	95	90	TBD
Blade length (m)	54.65	58.5	66	61.5	80
Tip Height (m)	125	150	162.5	153	TBD
Max Water Depth	25	up to 30m	up to 25m	up to 25m	up to 35m

Table 1: Technical summary of turbines used within this investigation

3. Substructures

3.1 Substructure Types

Common support structures for offshore wind turbines are categorized by the configuration and method of installation.

3.1.1 Gravity Base Structures

These are concrete shells that resist all other loads exerted upon it by the means of its own gravity; they must have resistance against sliding and sufficient vertical bearing capacity. Extra weight can be added to the base to give extra balance to the structure. They are commonly used in areas where pile driving is difficult such as hard rock ledges or component soil sites in shallow waters but they do require ground conditions to be prepared before installation. Gravity base structures (GBS) are the most cost-effective option when the environmental loading is low and the dead load is significant (Malhotra, 2011), however they can be extremely susceptible to scour and undermining due to their large diameter.

3.1.2 Monopiles

These foundations are a simple design of large diameter (4-6m) steel pipe driven into the seabed by large impact or vibratory hammers or grouted into sockets drilled into rock, the wind tower is then directly attached or a transition piece is used. Due to its reduced footprint size compared to gravity structures, the monopile has a smaller, more localized environmental impact; however as turbines get beyond 6MW, pile diameters become quite large necessitating heavy hammers, the availability of which could cause problems of practicality. Extensive scour protection is needed for this type of base structure.

3.1.3 Jacket foundations

Jacket foundations are constructed with a three or four legged steel lattice that is attached to the seabed with piles at each leg section. Legs have a diameter between 1 – 1.4m. They require extensive preparation of the sea bed before installation, with the pile holes being pre hammered rather than post hammered, they are utilised for turbines exceeding 5MW in depths between 15m – 80m, they are not utilised for smaller turbines as economics dictates that they are expensive to manufacture and require specialised transportation and lifting gear for installation offshore.

3.1.4 Guyed Monopile Towers & Tripods

Guyed Monopile Towers are used in deeper waters to limit the excessive deflection of a monopile which is achieved by stabilization by tensioned guy wires.

Tripods are used to limit the deflections of wind towers where guyed towers are not feasible. A triangular frame made of steel pipes 1.0 – 5.0m in diameter and is connected to a jacket leg in three corners, diagonally connecting horizontal braces onto a transition piece in the centre. These are anchored by drilled piles with a diameter between 0.8m – 2.5m.The biggest advantage of tripods is that they do not require any seabed preparation and they are of similar size and types to structures already present offshore and therefore installation is more familiar.

3.1.5 Braced Lattice Frames

Braced Lattice Frames have more structural members than a tripod frame, although it also consists of a 3 or 4 leg structure interconnected to provide the required support. The lattice design continues up the tower to the nacelle, rather than the base being connected to a transition piece. This basis truss structure provides stability and strength. This allows the towers to be prefabricated onshore, with more reliable welding, faster production and lower costs however scour protection is harder to install around the legs and the inner part of the structure as it's harder to reach.

3.1.6 Floating Tension Leg

Floating Tension Leg platforms are partially submerged by tensioning the vertical anchor legs to help repress the motion of the system. Installation is relatively simple compared with other options as the structure can be floated out to the site and connected to anchor piles or suction caissons and then lowered by ballast tanks or tension systems. Another advantage is that if there is any major maintenance required on the turbine, the entire structure can be disconnected from the anchor plates and floated back to shore.

3.1.7 Suction buckets

Suction buckets are lowered down onto the seabed and whilst the weight of the caisson is enough to cut into the seabed, it is not enough to push it to a sufficient depth and so a suction is applied by pumping the water held within the caisson to create a pressure difference between the caisson and the sea. This process is more effective in clay soils than in sand and requires a large surface area, however the penetration is less than that of a gravity base. The design of suction buckets is approximately half the weight of the steel used to construct a pile foundation and is easier to install and decommission (Ibsen et al., 2012) which therefore brings financial savings, as well as no hammering required so no noise mitigation techniques with therefore be required during installation, however they do require extensive scour protection. As there is no onshore equivalent to this technology, it is in its relative infancy compared with other methods.

3.1.8 Floating structures

Floating structures rely on their own buoyancy to keep them upright; however the continual motion of the sea exerts extra pressure on the structure. They are not restricted by seabed conditions and could prove useful in deep water. Several concepts for floating turbines are at the testing stage, these include ballast stabilised, mooring line stabilised and buoyancy stabilised (Lackner et al., 2011). Floating turbines are easy to install and decommission but they also have the added advantage of being easy to tow ashore should any extensive maintenance be required during the turbines operational lifetime.

3.2 Water depth and distance to shore

Wind turbine developments are moving further offshore and into deeper waters. In 2012 the average water depth of wind farms in Europe was 22m, with the average distance to shore being 29km. Projects under construction, consented or planned are showing a clear trend that average water depths and distances to shore are increasing (Figure 5), with projects being as far out as 200km and up to depths of up to 215m (EWEA, 2013).

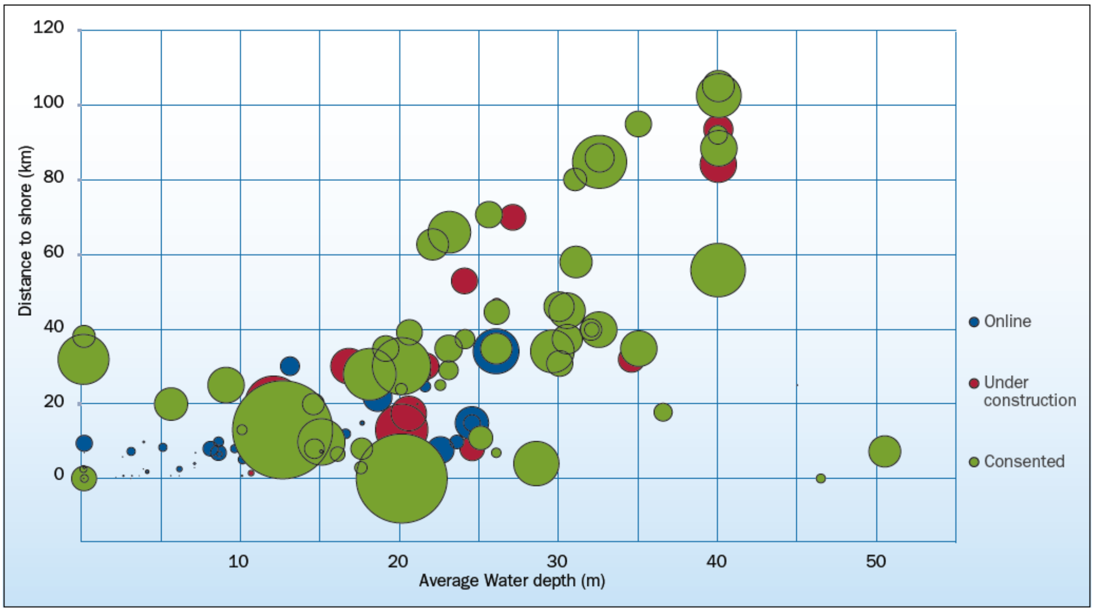

Figure 5: Water depths and distance to shore (EWEA 2013)

With the increase in turbine size, and with deeper waters, foundation dimension also increases, leading to new concepts for support options, other than those already established for other offshore structures like oil and gas exploration units, under water pipelines, bridges on the sea bed and port structures (Singh et al., 2010).

3.3 Loading and Resonance

When the offshore is in operation, the blades create vibrations as they pass the tower to which the whole structure is sensitive. As a three bladed rotor encounters a turbulent eddy it resists peak forces at frequencies of 1P and 3P, where P is the blade passing frequency (Figure 6). The blade passing frequency for a typical variable speed turbine is between the approximate range of 0.18Hz and 0.26Hz, with a rotation frequency between 0.54Hz and 0.78Hz (Malhotra, 2011), whilst cyclic loading from the sea waves occurs at a frequency between 0.04 Hz and 0.34Hz (Gaythwaite, 1990). The turbine, tower, support structure and foundation have to be designed with a natural frequency that is different from the rotor and wave frequencies to avoid resonance. Turbines with larger diameters require taller towers and bigger, heavier nacelles. The range of 1P and 3P increases linearly with blade diameter (Malhotra, 2011).

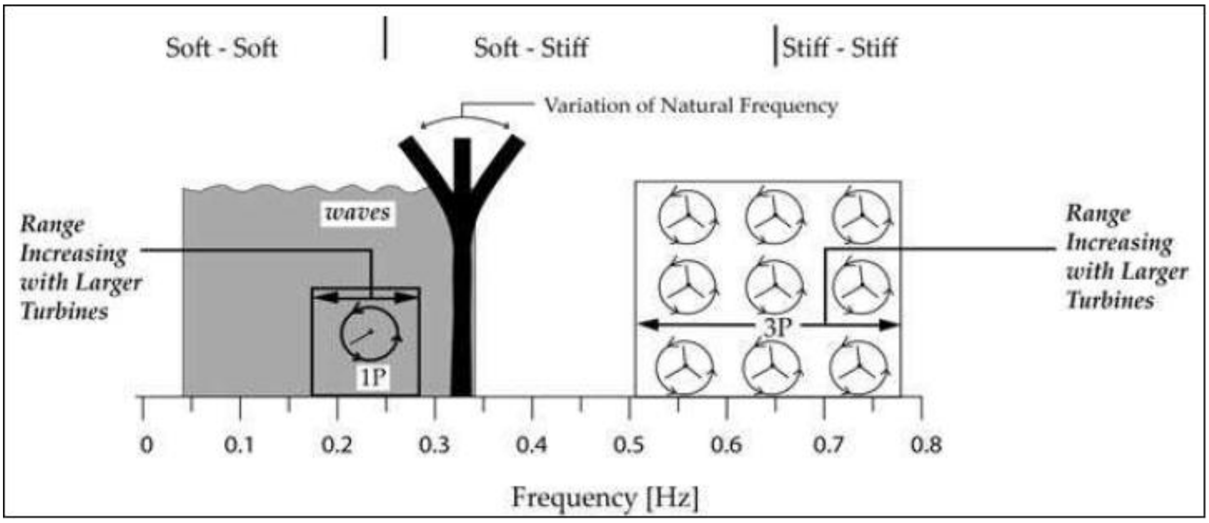

Figure 6: Typical ranges for frequencies of waves, rotors, blade passing and structure (Malhotra, 2011)

3.3.1 Environmental Loading

Environmental loading should also be considered, this can occur through wind, hydrodynamic (wave), ice and currents as well as seismic leads for those turbines that are located in seismic areas and can be time dependent; varying from a fraction of a second to several hours, acting on the wind tower through different load combinations and directions, and are resolved into an axial force, horizontal base shear, an overturning moment and torsional moment to be resisted by the foundation (Malhotra, 2011).

3.4 Costs

For deeper waters, the stiffness of the foundation and support structure plays a large role; this is due to the natural frequency of the tower system being inversely proportional to the height of the tower squared (Malhorta, 2011). Greater demands are put on the design of the foundation as the frequency of the higher towers decrease rapidly and thus fall into the region of wave frequencies. The cost therefore rises for foundations in deeper waters, not just due to the length of the support structure required to give the blades enough clearance above sea level, but also because the materials need to change to make the foundations extremely stiff compared with the more flexible foundations installed in shallow waters.

Cost of fabrication of the base structure and availability of materials can be a deciding factor when determining what type of base structure to use. The ease of construction should also be considered, including installation logistics and availability of experienced installers

3.5 Chosen Foundations

Of all the foundations that are available on the market, only three types consistently appear in environmental statements for commercial developments in the UK. These are jacket, monopile and gravity base (Figure 7). The main reason for this is that they are already tried and tested technologies of historical offshore structures and therefore their reliability is known. Tripile and tripod foundations are mainly used for testing facilities.

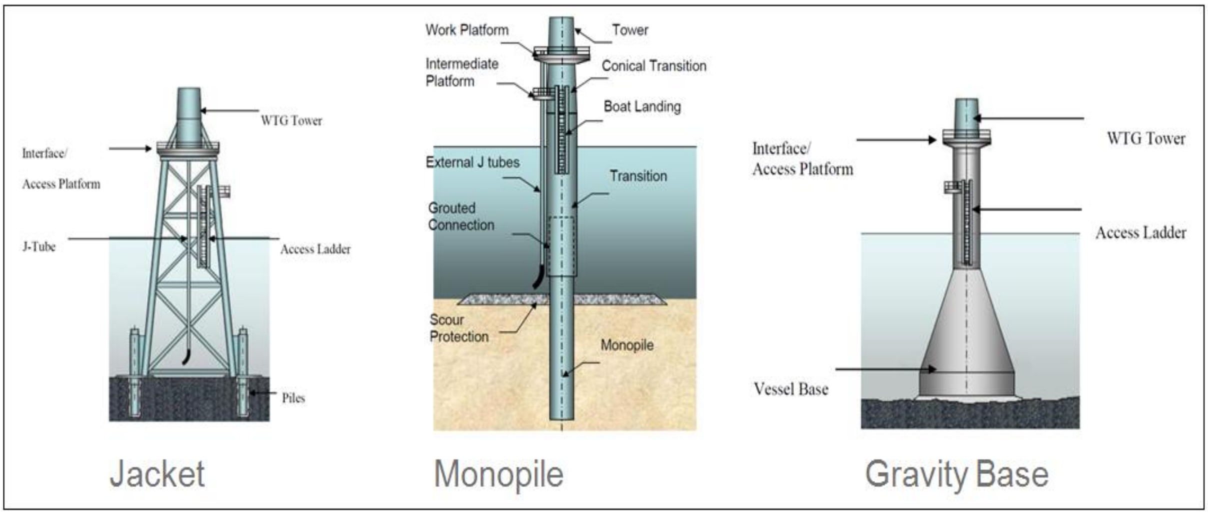

Figure 7: Base foundations used in this investigation (adapted from IMECHE, 2010)

Monopile substructures were the most popular type installed in 2012, with 355 in total which represents 13% of all newly installed substructures. Tripods represent a 6% share and tripiles 5%. Gravity based foundations represent 4% with 16 installed (Figure 8).

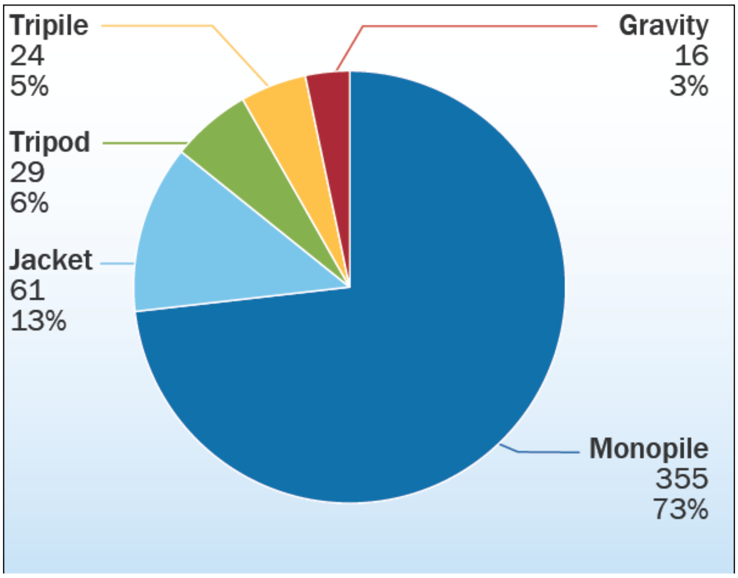

Figure 8: Distribution of foundation types (EWEA 2013)

4. Quantitative Analysis of Environmental Statements

4.1 Evaluation Methods

The need for a development has been well established in terms of economic benefit, and the relationship between money spent and money gained has been analysed before the proposal is put forward to the next stage. The ES details the effect of the proposed development on the environment, it is a collaboration of physical scientists, social scientists and engineers and ensures that previously un-quantified environmental amenities and values are given appropriate consideration in decision making. This type of analysis does not produce an overall quantitative rating which would allow a system for the analysis and numerical weighting of probably impacts but is a combination of scientific research and expert judgements (Leopold et al., 1971). As this research is based around comparing the impacts of one project against another, a method had to be found by which each component of an environmental statement could be compared numerically and with scientific objectivity for justification of choice of development that ensures that the impacts of alternative actions is evaluated and considered.

In the composition of an ES, many techniques have been developed in order to quantify the contribution each indicator has on the final outcome. Although the environmental impacts of each stage of the project is well documented in an ES, it is very difficult to quantify these impacts and compare them as they are mainly subjective, those that do have a scientific underpinning lack any real clarity as it is difficult to compare the effects with those of an alternative solution as it is unlikely that the measurement if impact is the same for two solutions. There is a need for a scientific basis to fully understand the differences between alternative construction solutions, there therefore needs to be a method devised thet allows an explicit procedure to be performed for a weighting to be given between different categories.

There is no single ‘gold standard’ method that is applicable to all situations, methods can be goal and scope dependent (Goedkoop et al., 2012). Evaluation procedures should be systematic, simple to follow and easily replicable to enable others to undertake the same procedure and obtain similar results (McAllister, 1995).

Confidence limits are needed with the information and methods used in Environmental Impact Assessments, this allows the uncertainty to be quantified. If the confidence limits are high, then the answer given is highly likely to be within the given parameters.

Environmental and social impacts such as aesthetics and human interest that are difficult to quantify are known as intangibles (McAllister, 1995). It is important that these are recognised in this analysis alongside quantifiable impacts. Environmental evaluation can also express values that cannot be conveyed in numerical ratings, though they can be conveyed by giving a value of importance (McAllister, 1995). Environmental evaluations must also be capable of respecting the changing views of interest, ethics and legislation over time.

4.1.1 Checklists

Checklists were the earliest form of identifying where weakness’ lay within an environmental report by providing a list of common or likely effects. They are particularly valuable for analyzing cumulative effects because they,

> “*provide a format for juxtaposing multiple actions and resources in a way that highlights potentially cumulative effects*” (NEPA, 1997),

however they have the disadvantage of not specifying at what level the information should be presented, therefore they can be incomplete or contain too much information, often double counting the same effects under different headings. They are very development specific as they do not provide a quantitative analysis that can be compared with other developments. In order to determine the effect that the project is having on the existing environment is to compare the predicted quality of the environment once the project is in place, with the current environmental conditions.

4.1.2 Matrices

Matrices are two-dimensional checklists designed to assess the magnitude and importance on individual interactions between activities and resources (Leopold et al., 1971) and can be extended to consider the cumulative effects of multiple actions (LaGory et al., 1993). The matrix approach is distinguished from checklists as they incorporate an association between cause and effect. Matrices do not provide a quantification of effects on their own, but can be used in conjunction with modelling, mapping and subjective techniques to manipulate results, including very complex data as they have the advantage of being mathematically straightforward and readily responsive to interpretation (NEPA, 1997). This technique can be used in binary form to note the presence of an effect or not, but this does not allow for any measurement of magnitude or contain any value for the importance of a resource. Therefore analysis can score effects based on factors such as magnitude, importance, duration, probability of occurrence and feasibility of mitigation (NEPA, 1997) which allows a measurable value to be input which allows the user to trace resource effects. Matrices can be extended to stepped matrices that can present resources against other resources (Canter, 1996) which address secondary and tertiary effects.

The disadvantage of matrices is that is it hard to use a scientifically reasonable means to quantify values, especially one that can be easily replicated by other scientists or can be understood by someone out with the project team. Weighing schemes are highly subjective and often the ranking criterion is not scientifically reasonable to conduct a comparison of cumulative effects (NEPA, 1997).

4.1.3 Graphical Representation

If long term historical data is available, trend analysis provides a method by which resources, ecosystems and human communities interact over time, and changes can be quantified and presented in a graphical manner to help project future conditions. Three steps are involved; identifying cumulative effect problems, establishing appropriate environmental baselines and projecting future cumulative effects (NEPA, 1997) it can also be useful in revealing threshold points where cumulative effects become significant when data is lacking or unavailable. Unfortunately in order to carry out trend analysis, data has to be available in abundance for every variable so that the results can be scientifically valid, and the separation of resources can obscure cumulative effects.

4.1.4 Life Cycle Analysis

It is possible to look towards Life Cycle Assessment (LCA) as a tool for detailed quantitative analysis in the field of environmental strategic decision making. LCA can help resolve one environmental issue whilst avoiding the creation of another, known as “shifting of burdens” (EU, 2010). LCA is a structured, internationally standardised method and management tool (ISO 14040 and 14044, 2006) to promote sustainable development and to evaluate the environment. LCA proceeds through two mandatory steps; selection of impact categories relevant to the study and characterise the impact quantitatively according to the underlying environmental mechanism (EU, 2010). This allows the impact to be expressed as an impact score in a unit that is common to all the contributing indicators within the impact category.

There are also two optional steps within LCA that are particularly relevant to this study; impact scores between categories can be compared when the different characterised scores are normalised and become related to a common reference (EU, 2010) and weighting can be applied to different environmental impact categories to reflect the relative importance of impacts to realise the trade-off situations that could occur between different processes (EU, 2010).

Life cycle assessment (LCA) of renewable energy projects, specifically wind turbines both on and offshore is well documented (Lenzen et al., 2002, Guezuraga et al., 2012, Arvesen et al., 2012, Crawford, 2009) but it is important to distinguish between life cycle analysis and the impact analysis at any point in time. In this study the aim is to quantify the impact of turbines with variables changing depending on those selected within the model. From these we know that it only takes a few months for carbon payback of RE systems, and is greater when compared with fossil fuel alternatives, this includes indicators of extraction of raw materials, manufacture of components, transport, on-site construction and operation and maintenance as well as decommissioning are all normally included within a LCA.

Whilst this study is not concerned about the whole life cycle of a development, it has to be considered that LCA can provide a method by which each individual impact can be quantified. This includes the impact upon the soft constraints; ornithology, marine mammals, fish, and benthic habitats, physical processes (sediment), land use (i.e. footprint – eco indicator dictated that the more land that is used, the higher the eco-indicator), and particulate matter formation (i.e. scouring).

The Dutch are especially good at devising LCA methods; in 1992 the CML LCA-guide (Centrum Milieukunde Leiden) marked a breakthrough in the scientific foundation of LCA methodology (Goedkoop et al., 2012) followed by Eco-indicator 95 and Eco-indicator 99 which builds upon these methodologies. The latest version, ReCiPe (named after the collaborative universities RIVM and Radboud University, CML and Pre) was released in 2012.

These methods are revolutionary as they aggregate LCA results into easily understandable and user friendly numbers or units known as “eco-indicators”; the unit is milli-point (mPt) e.g. 700mPt = 0.7Pt, with 1Pt being equal to a thousandth of yearly environmental load of one average European inhabitant (Ministry of Housing, Spatial Planning and the Environment, 2000) allowing a single score to be calculated from many environmental effects. ReCiPe has also collected data for the most common materials and processes and indicated the environmental impact of these, allowing a picture to be built of the impact to be made depending on the final indicator number (low = good, high = bad). The ReCipe looked like the ideal tool to calculate mid-point and end point effects of building an offshore wind farm compared to the baseline, however although some subjective impacts were included that were not included in the checklist or matrix techniques as managing different perspectives where there was no objective method before, unfortunately the method did not include any methodology for the effect of noise (Goedkoop et al., 2012).

Noise is often omitted from LCA, reasons cited include that they are taken care of elsewhere in Environmental Analysis by other tools that can calculate their effect more accurately (Ghenai, 2012, D’Souza, 2011) or no damage models exist to accurately quantify cause and effect (Castro et al., 2011). As acoustic effects make up a large part of any offshore wind development, this was an important consideration as it is something that has guidelines and boundaries within an EIA and has to be quantified and taken into account when developing a windfarm under EU legislation. Due to the time constraints of this project, it was not possible to devise a separate calculation to include acoustic interference with marine life from the different methods of turbine base installation and align these with the methodologies presented within this framework.

4.1.5 Environmental Evaluation System

The Environmental Evaluation System (EES) was devised by a global research and development organisation based in Ohio, United States, to assess the impact of water resource developments, water-quality management plans, highways, nuclear power plants and various other projects that could potentially impede on the environmental quality of water (Dee et al., 1972). Environmental impacts are quantified and aggregated into "environmental quality units" (Baggs, 1983) allowing an analysis of different planning/design options to be compared, it also requires an assessment of conditions before any project is implemented, in order to give a comparison of environmental effects compared to the base case as well as a measure of how the current conditions compare with good environmental quality. The EES also allows changes in legislation over time to be taken into account by way of a weighting process which is overseen by a group of experts.

The EES was found to be the most suitable technique as it took into account both objective and subjective parameters, and also, crucially, incorporated the effects of noise within the calculation. Providing a dynamic, sound solution to assessing the cumulative impacts of different parameters in offshore developments.

4.2 Method

In the original EES there were 78 environmental factors identified by the Battelle System called Basic Environmental Parameters (BEPs), nineteen Intermediate Environmental Components (IEC) and then into four General Environment Categories (GEC); ecology, aesthetics, physical/chemical and human interest/social. These parameters are considered to be of crucial importance when considering an environmental impact assessment (Rogers, 2001) and were selected using a screening process on the basis of their significance. In order for each parameter to be expressed in a quantitative terms, impact measurements of the environmental parameter were measured. This allows different options to be compared against one another to assess the impact of one solution against another.

To summarise and compare impacts, the parameters are weighted so that they can be related to one another in terms of importance to the project. This allows a sum of all impacts to be made for each alternative design within a project and the totals can be compared. This was originally carried out by Dee et al., (1972) by distributing 1000 Parameter Importance Units (PIUs) among the parameters, thus representing the relative importance of the listed parameters for a development.

It is also important that a weight should be assigned to indicators composing the synthesis, with the choice of weights derived from an objective principle (Hagerty et al., 2007), this allows a suitable statistical approach to ecosystem indicators which are most likely to have an effect on the environment should the situation change whilst understanding thet all measured indicators do not contribute the same weight to the final outcome. This weight should theoretically reproduce as accurately as possible the contribution of each sub-score to the construction of the synthetic score (Maggino et al., 2009) and ensures that the quality of the data and the statistical adequacy of the indicators is kept intact.

The measurement of environmental quality is undertaken by finding a 'value function' for each parameter. Where parameters are quantifiable and therefore have a scientific grounding, this is a relatively simple process; the current environmental quality is found and the projected environmental quality which would be present after the implementation of the project is measured. This is undertaken for all possible design scenarios for each of the parameters. This information is then normalized to obtain an Environmental Quality (EQ) scale whereupon 0 is 'very good' and 1 is 'very bad'. Those which are found to be close to zero do not represent any significant changes to the environmental quality from what is already present, whereas those which have a measurement which is nearer to 1, implies that levels are at or close to those permissible by law. The process of normalizing each parameter is necessary as it allows the data to be compared fairly and the output number is a parameter quality score.

The next stage of the process is to multiply each of the parameter quality scores with PIU weighting that was assigned to the parameter; the output value is a score in Environmental Quality Units (EQUs).

$$EQU = EQ \ X \ PIU$$

The final stage is to sum all of the individual EQUs to give a total score for the project using a particular design. This can be done several times over to compare the impacts of different designs to see which components exert the most influence. The project with the smallest total the end, has the least environmental impact and can be quantified against the current environmental quality. This also allows different project designs to be ranked, in preference of least environmental impact.

The advantage of using the EES is that the parameters can be changed on the basis of what is important for a particular project. For this study, 4 environmental statements for offshore wind farms were analysed and 72 basic environmental parameters were identified in 16 intermediate components in 3 general categories (Table 2).

Weighting was carried out by asking a panel of 6 experts within an offshore wind development team to distribute 1000 PIUs between the listed parameters. A meeting was held whereby a short presentation was given to demonstrate how to carry out the task; each expert was asked to use their expert judgement in weighting the parameters, whilst not discussing it with their neighbour as this would skew the scores. Once information had been collected from all members of the panel, the weightings were averaged out across each parameter. There was found not to be any major differences between weighting assigned by each of the panel members to the parameters, small variations were only found where panel members had a particular specialism in one field and therefore favoured its importance within the project.

The top five constraints that were deemed most important using the weighting method were all hard constraints;

- Oil and Gas Pipelines and Platforms - 40
- Civil Aviation: Airspace - 38
- Civil Aviation: Aerodromes - 38
- Trans boundary International Air -38
- Air Defence and Military Operations (MOD) -38

The reason that hard constraints take precedence over the environmental factors is due to the economy and state security; oil and gas exploration is worth far more to the government than renewable energy projects in terms of monetary return from taxes and export. Aviation also plays a large part; large turbine blades cause signal loss in radar reception which can be catastrophic to international communications. As flight paths and aerodromes are already in situ, it is easier to adapt the design of a wind farm to reduce or eliminate the interference, or in some cases where the military will be affected, developments are refused permission altogether.

The top 5 environmental parameters were;

- Importance of site for birds - 27
- Designated Sites (SPA, Ramsar) - 23
- Underwater Noise - 22
- Species of Conservation Interest - 18
- Spawning and Nursery Grounds - 18

Collision risk factor for birds is an important consideration for windfarm sites, several modelling techniques have been utilised to try and determine flight heights for different species and potential collision- related mortality (Cook et al, 2012) and sites can be deemed inappropriate for development if certain protected species either nest in the surrounding area, or it is part of their migration flight path. Second to this are designated sites such as Special Protected Areas (SPA) or Ramsar, both of which are concerned with protected species and their habitat. Developments on or near habitats of these species will either have to be designed so that minimal disturbance is exerted upon the area, or habitat compensation occurs elsewhere. If too great a disturbance is expected, the whole project could be called off, this is also true of species of conservation interest and spawning and nursery grounds.

Underwater noise is a big factor in offshore developments, noise to install turbines is far greater than airborne noise onshore as the installation process requires larger foundations to be installed, usually by much more aggressive methods than would be required on land, this could have a knock on effect to species of conservation interest and designated sites. The choice of turbine foundation also affects spawning and nursery grounds due to the footprint size, which could be much larger of scour protection is required.

For each of the measurable parameters, a common environmental baseline was found within the 4 environmental statements used to define the parameters; the upper limit was defined by that permissible by law, or by a European Directive. The upper limit captures everything within the Rochdale envelope – it is the maximum level that is allowed by law/guidelines and is therefore used as a ‘worse-case’ scenario. This allows a massive flexibility of design within the assessment. Three different base structures were plotted along this scale, with their impact being measured on both a temporal and spatial level. This allowed the three structures to be compared fairly in stages of installation, operation and decommissioning, as well as a value for pre development to be determined. These numbers were then normalised so that each parameter had a score of 0 which signified the environmental baseline, and scores up to 1 which signified the upper limit dictated by law. This was again repeated for the 5 turbine models.

Where parameters could not be easily defined by numerical means, the panel of experts were once again consulted as to the assignation of EQ scores, this was necessary for all of the parameters in the “Human Interest” section as these are down to non measureable means or by personal opinion. These were expressed qualitatively as shown in Table 3 with a number assigned to each value so that it could be expressed quantitatively.

Physical/Chemical (98)	Ecology (222)
Marine Geology, Oceanography and Physical Processes (36) - Water Level Regime (4) - Current Regime (5) - Wind Regime (5) - Sediment Regime (5) - Morphodymanic Regime (5) - Physical Process Receptors (eroding & -sensitive coast, offshore sandbanks with conservation designation, coastal and EU designated conservation sites, non-designated sand banks, recommended MCZ, seabed infrastructure (cables & pipelines)) (7) **Marine Water Quality (14)** - Temperature (2) - Salinity (2) - Nutrients (nitrate and phosphate) (2) - Dissolved Oxygen (2) - Hydrocarbons (2) - Spillage & contamination (2) - Heavy Metals (Ni, Cu, Zn, Cd, Pb, Hg) (2) - Bathing Water Quality (1) - Suspended Sediment (2) - Sediments (2) **Underwater Noise and Vibration (48)** - Ambient Noise (inc. Vessels) (2) - Electromagnetic Field Detection (6) - Underwater Noise (22) - Vibration (18)	**Benthic and Epibenthic Environment (including shellfish) (38)** - Benthic Surveys (3) - Sediment Composition (5) - Benthic Fauna (4) - Biotopes (4) - Epifauna (4) - Marine Protected Areas (17) **Fish Ecology (67)** -Natural Fish (5) - Spawning and Nursery Grounds (18) - Species of Conservation Interest (18) - Elasmobranches (5) - Prey Species and Food Web Linkages (5) - Demersal Species (5) - Pelagic Species(5) - Diadromous Migratory Species (5) **Marine Mammals (40)** - Pinnipeds (grey & harbour seal) (20) - Cetaceans (Whales, dolphins & porpoises) (20) **Ornithology, Marine and Coastal (62)** - Designated Sites (SPA, Ramsar) (23) - Seabird Abundance (12) - Importance of Site for Birds (27) **Airborne Noise (15)** - Onshore Receptors (15)

Human Interest/ Social & Aesthetics (680)

Socio Economics (80)

- Tourism (5)
- Recreation (5)
- Economic Activity & Employment (37)
- Occupation & Skills (33)

Archaeology and Cultural Heritage (40)

- Prehistoric Receptors (known and potential (12)
- Maritime Receptors (Known and potential (12)
- Aviation (known and potential) (16)

Infrastructure and Other Users (113)

- Other Windfarm and Renewable Energy Developments (10)
- Non-Aviation Military and MoD Issues (13)
- Unexploded Ordnance (35)
- Oil and Gas Pipelines and Platforms (40)

Subsea Cables (9)

-Dredging, Dumping and Disposal (6)

Shipping and Navigation (194)

- Navigational Features (38)
- Commercial Shipping (38)
- Recreational Vessel Activity (12)
- Fishing Vessel Activity (15)
- Search and Rescue Helicopters (38)
- Royal National Lifeboat Institute (15)
- Coastguard Stations (33)
- Maritime Incidents (4)

Commercial Fisheries (17)

-Fishing Activity (vessels, gear - longlines, fixed nets, drift nets, pots), operating patterns, effort and values) (17)

Aviation and MOD (170)

- Civil Aviation Airspace (38)
- Civil Aviation: Aerodromes (38)
- Trans boundary International Air(38)
- Air Defence and Military Operations (MOD) (38)
- Helicopter Operations (17)

Telecommunications and Interface (51)

- Maritime Radar (Vessel/O&G/Onshore) (26)
- Telecommunication Systems (Automatic - Identification System (AIS), VHF Radio, Radio Beacons, Distress Beacons, Fixed Links, GPS, Telephony, Television) (25)

Landscape, Seascape and Visual Impact (15)

- Landscape Character (Offshore/Landfall) (8)
- Key Visual Receptors (ferry passengers/merchant seamen/recreational sailors) (7)

Table 2: Seventy two basic environmental parameters were identified in 16 intermediate components in 3 general categories from examination of historical environmental statements

Significance	Definition
Major Beneficial	Provision of significant positive gain to the environment
Moderate Beneficial	The impact is of some gain to the environment
No Impact	Baseline conditions remain the same
Negligible	Slight change from baseline condition
Minor Adverse	Undesirable but is of no consequence
Moderate Adverse	Some concern over the impact, but deemed to be in acceptable limits
Major Adverse	Serious concern as unacceptable limits have been reach, mitigation required

Table 3: Parameters for subjective analysis

This also introduced a new concept that the quality of the baseline could be improved; employment was actually an improvement on what was present before the development took place. Therefore an element of "corporate responsibility" was included, providing a "beneficial" effect which was not seen in any other area.

It is important to note that this process takes into account both the impact and effect on a both a spatial and temporal scale for the three separate phases of development; installation, operation and decommissioning.

The process of assessing environmental impacts using the EES is illustrated in numeric form below;

$$E = \sum_{i=1}^{m} (v_i)_1 w_i - \sum_{i=1}^{m} (v_i)_2 \, w_i$$

Where:

E = environmental impact

$(v_i)_1$ = value in environmental quality units of parameter *i* with project (0 - 1)

$(v_1)_2$ = value in environmental quality units of parameter *i* without project (0 - 1)

w_i = relative weight of parameter *i*

m = total number of parameters

4.3 Results

Results are presented for each turbine type and for each corresponding base structure over the three stages of the project for 1 turbine; installation (expected to take 2 years), operation (expected to last 20 years) and decommissioning (expected to last 1 year). Using the EES, it can be seen that during all three phases, the larger the rated capacity of the turbine, the higher the environmental quality until associated with it (Figure 9/10/11). The Environmental Quality Units (EQUs) also indicate that the most intrusive part of the project is the installation phase, with the operational phase having less disturbance on the marine environment than both the installation and decommissioning phases.

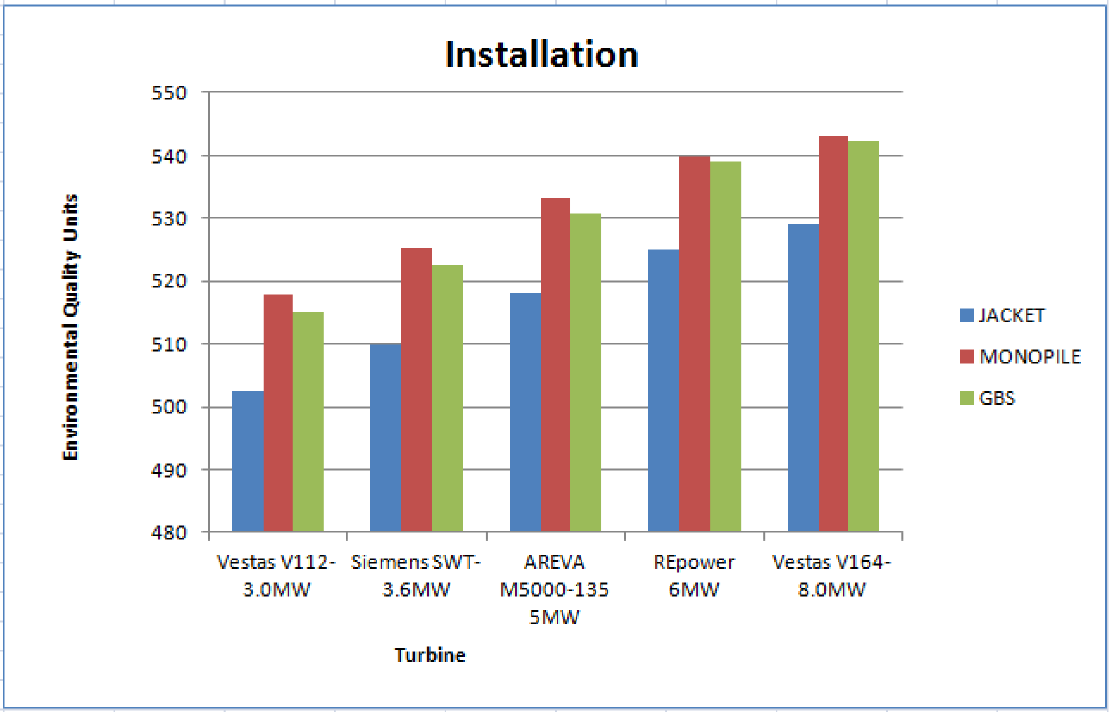

Figure 9: Installation of different turbines with corresponding base structures

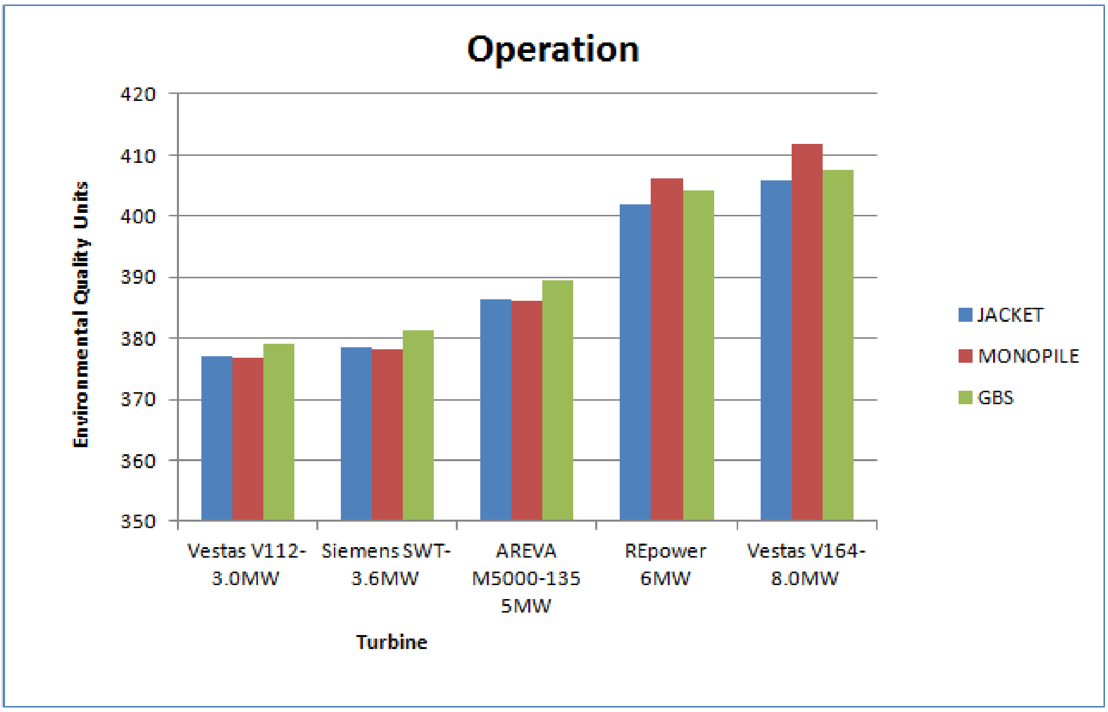

Figure 10: Operation of different turbines with corresponding base structures

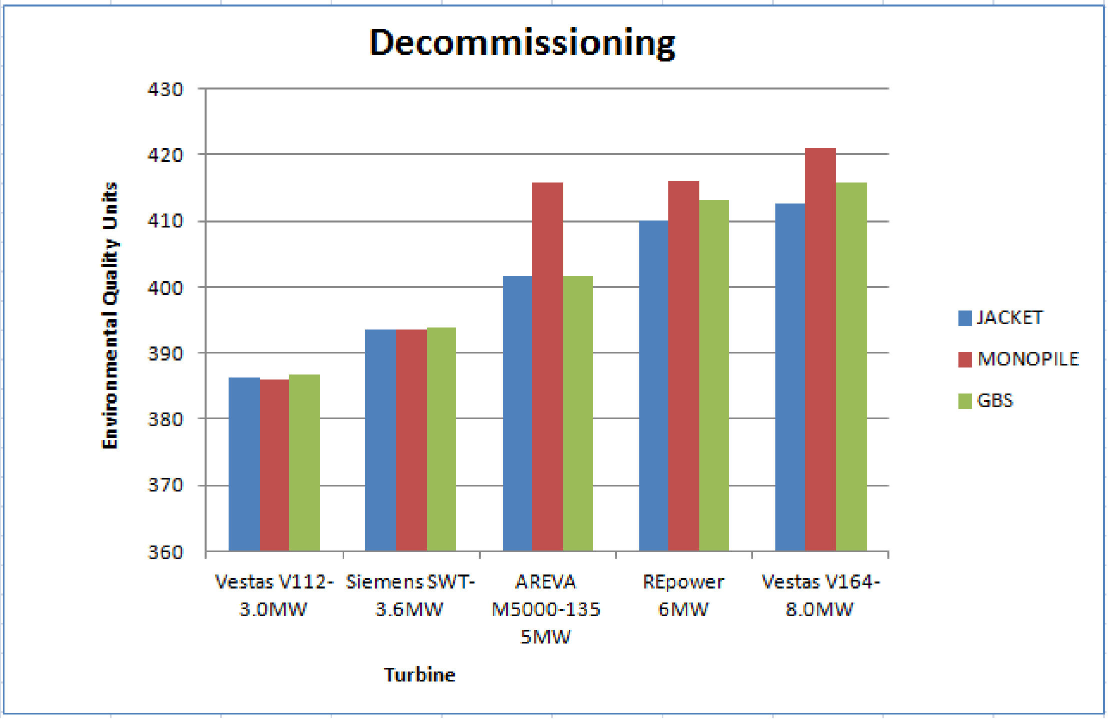

Figure 11: Decommissioning of different turbines with corresponding base structures

The differences between the different base structures was not quite as clear as turbine type. Generally monopile was the most detrimental to the environment for the installation phase, this is due to the high volumes of noise associated with pile driving, which will increase as the monopiles get larger to accommodate larger turbines. GBS closely followed monopiles as although there is less noise for installation, they have a large footprint on the seabed, smothering receptors and habitats and creating a larger obstacle for marine mammals. They also increase with turbine size. Jacket foundations generally created least disturbance, because although they do require some noise for installation of the pins to keep them in place, the pins are much smaller in diameter than monopiles. They also have a smaller footprint than GBS.

For the operational phase, the EQU is mainly dictated by the size of both the foundation and the turbine; a larger turbine creates a larger obstacle for both marine mammals and for human activities.

The decommissioning phase is again dictated mainly by noise and seabed disturbance, although this has not yet been practiced in UK waters, it is expected that the disturbance will be less than installation as no pile driving will be necessary and inter-array cables will be left in the seabed. This is reflected by the EQU's.

It is important to note that the three phases should be taken as individual studies as the totals shown are for different temporal scales; installation 2 years, operation 20 years and decommissioning 1 year.

4.3.1 Cumulative Impacts

The results presented above were for single turbines with either a jacket, monopile or gravity base foundation. The object of this exercise is to determine cumulative impacts and where problems arise.

As the installation phase creates most disturbance and had the highest impact according to the EES, it is appropriate to concentrate on this phase of the development for assessing cumulative impacts.

The EES was utilised to assess the impacts of a 60MW project (Figure 12) and a 500MW project (Figure 13) using different turbines and different bases to predict the overall impact exerted on the environment.

Turbine Type	No. of Turbines	GBS	MONOPILE	JACKET
Vestas V112-3.0MW	20	10300	10358	10051
Siemens SWT-3.6MW	17	8883	8928	8670
AREVA M5000-135 5MW	12	6368	6400	6219
REpower 6MW	10	5391	5398	5250
Vestas V164-8.0MW	8	4067	4074	3969

Table 4: Turbines and impact of 60MW development during the installation phase

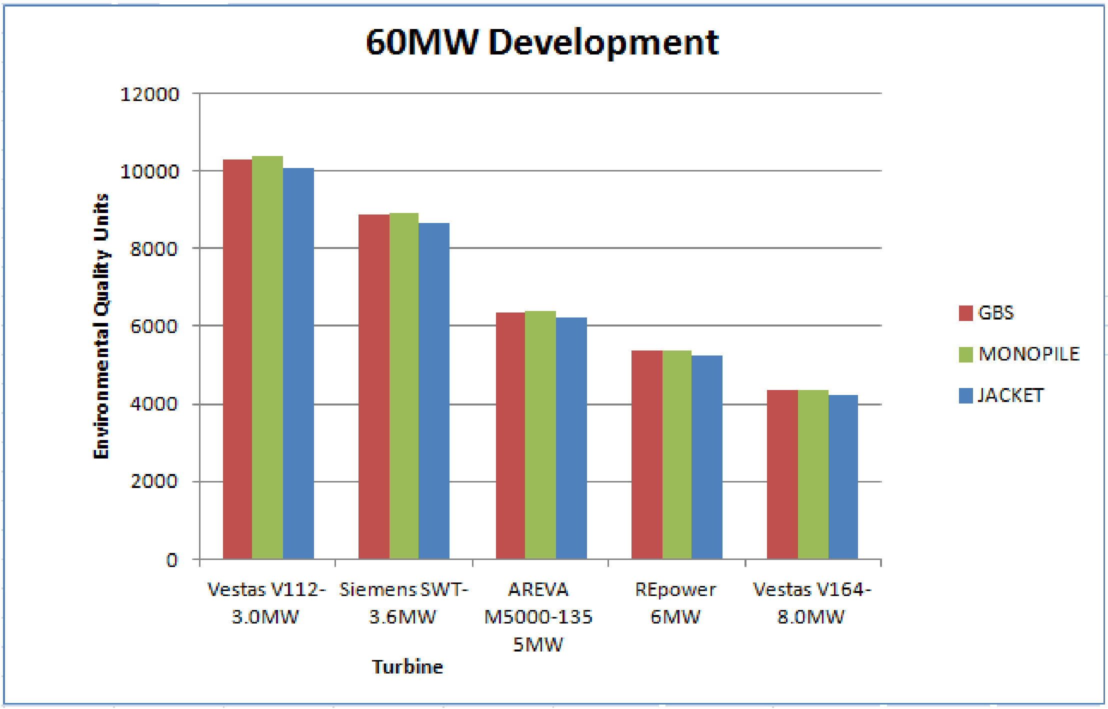

Figure 12: Cumulative impact of 60MW development

As the rated capacity of turbines increases, there are less of them required to be installed to meet the development capacity, therefore the overall disturbance within the development area is reduced.

The offshore wind development Alpha Ventus in Germany was commissioned in 2010, this was a 60MW project using the Areva M5000 5MW turbine using a jacket foundation, this would have had 6219 EQU, to reach this same capacity using the Vestas V164 8MW turbine with a jacket foundation would have had 3969 EQU. Even though the foundation type remains the same, simply reducing the turbine numbers whilst still reaching the project rated capacity gives a massive reduction on the disturbance to the environment.

This is further demonstrated by using a 500MW example, to reach this capacity using Vestas V112 3MW turbines there will need to be 167 installed, if using a monopile base this would be 86489 EQU, whereas to reach the same capacity using the Vestas V164 8MW turbine, only 63 will need to installed, and using the monopile foundation will give a value of 34222 EQU (Table 5, Figure 13).

Turbine Type	No. of Turbines	GBS	MONOPILE	JACKET
Vestas V112-3.0MW	167	86005	86489	83929
Siemens SWT-3.6MW	139	72628	73003	70891
AREVA M5000-135 5MW	100	53070	53330	51822
REpower 6MW	84	45284	45343	44102
Vestas V164-8.0MW	63	34165	34222	33338

Table 5: Turbines and impact of 500MW development during the installation phase

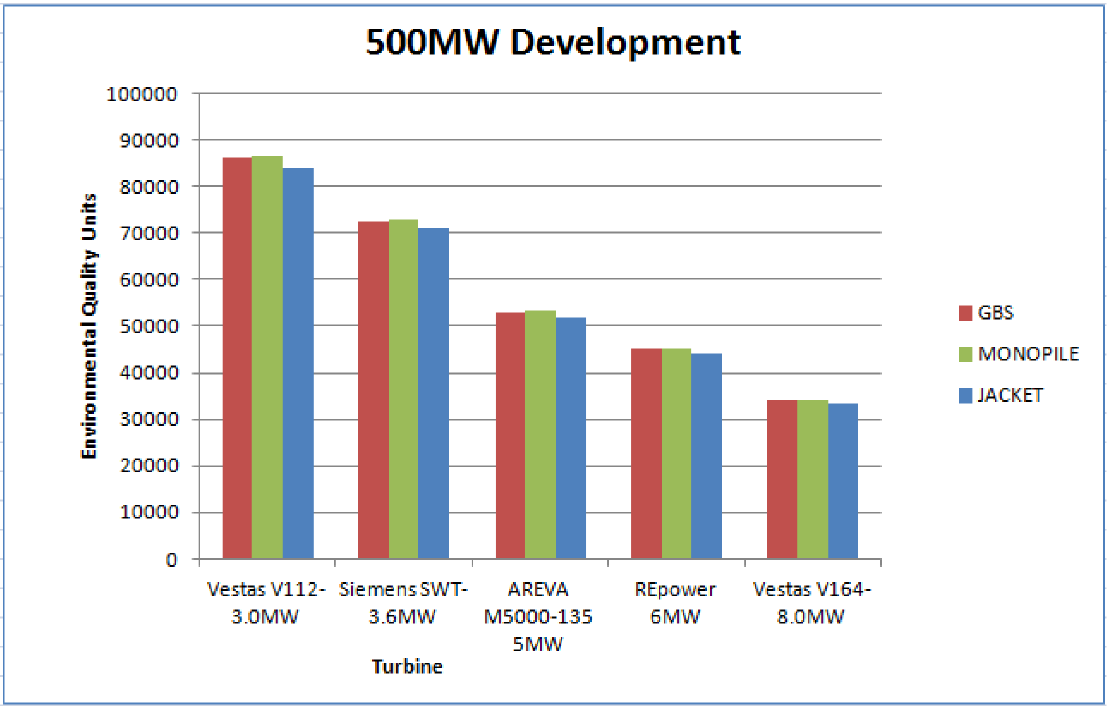

Figure 13: Cumulative impact of 500MW development

For many of the human factors, it is impossible to determine an exact figure for the cumulative impact due to the subjective nature of the topic, therefore multiplying the answer for 1 turbine in the landscape, seascape and visual impacts is not necessarily applicable when more are present, is possible that there would be an acceptable threshold which is impossible to determine quantitatively. This is also correct for Shipping and Navigation and Aviation where there would be an unacceptable threshold.

However using the EES gives a clear indication that using less turbines is more beneficial to the environment, whilst still maintaining the development rated capacity. The differences between the foundation types is also important as it allows different design options to be considered.

In order to understand the cumulative impacts in more detail, the sum of each environmental parameter can be examined to see where it will fall along the scale of acceptability. This will give an indication of the size of the Rochdale Envelope that should be used when writing the ES, and also will flag up where any problems might arise where upper thresholds will be breached.

However, it is not just the environmental considerations that are taken into account when constructing large developments; engineering and economic factors are also important. The following sections explore two environmental effects that occur during the installation of foundations and the mitigation measures needed to ensure that minimal harm is exerted on the surrounding environment, and discuss the engineering required and the costs associated with each option.

Noise is examined first, as was seen in the expert weighting, underwater noise is crucial to the consenting process; the choice of foundation severely impacts on the noise that will be emitted during the construction phase of the development and could impact greatly on protected species, mammals and fish.

The second impact examined is scour. If scour is found to be an issue at a foundation, it will have an effect of smothering spawning and nursery grounds which were highlighted during the weighting process as a major cumulative impact. If scour protection is installed to protect against undercutting of the foundation which will impact on the loading of the turbine, a larger footprint will be required which can majorly affect protected species habitats.

5. Installation Noise

5.1 Noise

There is always a high level of background noise in sea water (Figure 14) due to both natural sources of noise such as turbulent fluctuations in the sea state or manmade such as ocean traffic. Sound propagates over longer distances than it would in air, with the speed of sound in water reaching 1500m/s compared to 340m/s in air. As was seen during the expert weighting process during the EES, underwater noise is an important component to any EIA undertaken for an offshore windfarm; the choice of foundation severely impacts on the noise that will be emitted during the construction phase of the development and could impact greatly on protected species, marine mammals, fish and spawning grounds, all of which were weighted highly using the EES. Therefore if a foundation is found to be too noisy to install, especially with a larger turbine size necessitating a larger foundation, a different foundation type will have to be used, which could have technical and economic implications that are detrimental to the project.

Piling for offshore installations is one of the highest sources of underwater noise (Madsen et al., 2006), followed by shipping and seismic surveys. It is important to realise that although the wind farms are consented, steps have to be taken to minimise the effects of pile driving on the surrounding environment. There are legislative provisions that have to be complied with when working on the United Kingdom Continental Shelf such as The Conservation of Habitats and Species (2010) and the Offshore Marine Conservation (Natural Habitats) Regulations (2007) which was amended in 2009 and 2010 to include the Offshore Marine Regulations. Full comprehension of how marine mammals interact to pile driving noise is lacking, however the Joint Nature Conservation Council (JNCC), Natural England (NE) and the Countryside Council for Wales (CCW) provide guidance, recommendations and protocols that should be considered “best practice” for piling operations (JNCC, 2010).

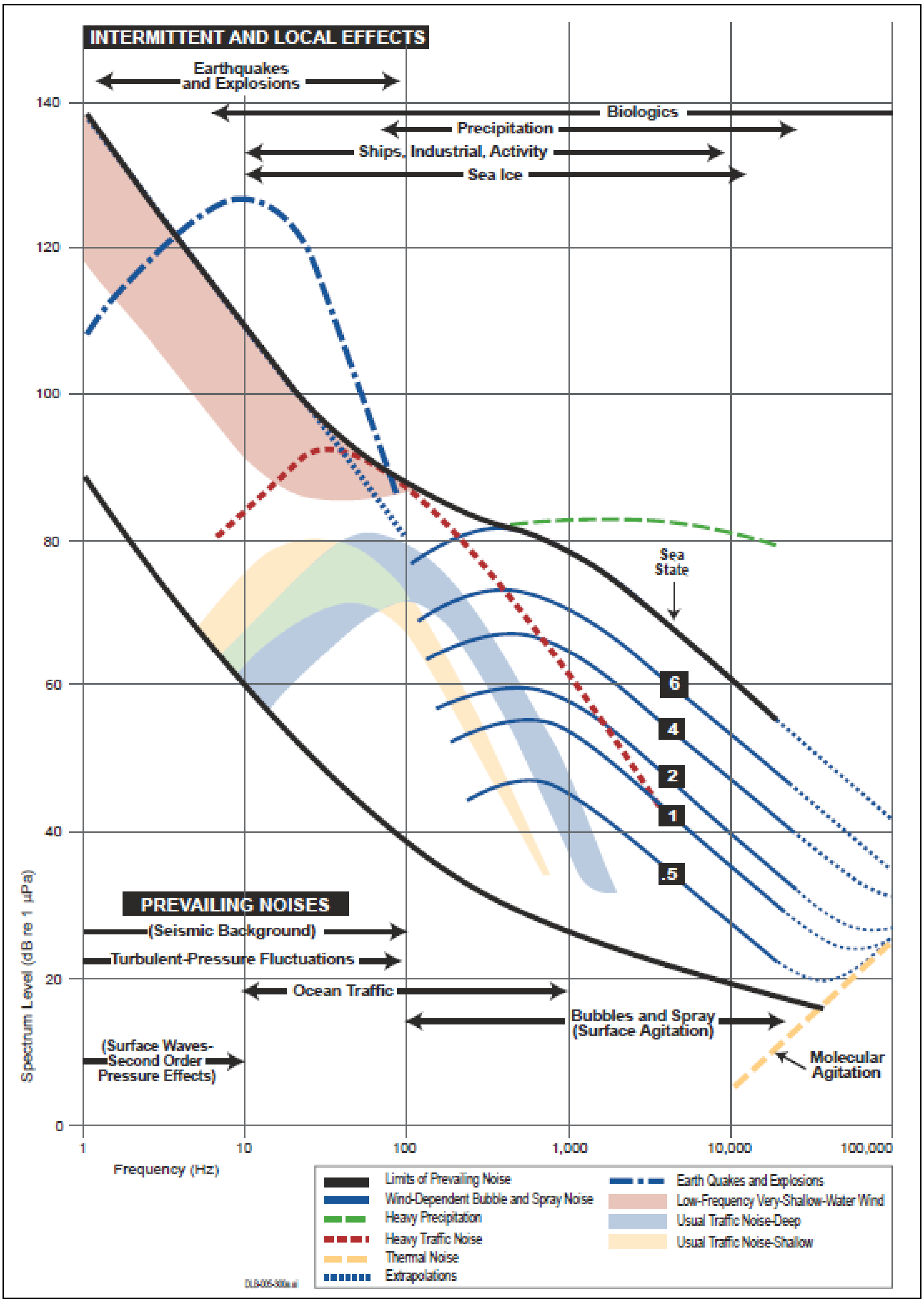

Figure 14: Different types of noise found in the ocean, extending from 1Hz to 100 kHz (Bradley et al., 2008)

5.2 Noise Disturbance

Installation of offshore wind turbines, particularly piling for both monopiles and pin piles for jacket foundations, without any mitigation, is likely to create a disturbance to fish and marine mammals. Hearing is particularly important for marine mammals as it is used as a means of communication, to locate prey, conspecifics and predators (Richardson et al., 1995). Therefore a change in sound levels within the marine environment can have a profound effect on the animals; it could lead to a temporary shift in hearing thresholds, or even injury or death. It could also lead to avoidance of feeding grounds for prolonged periods of time.

Each species has its own sensitivity and hearing range, therefore it is difficult to both quantify thresholds and mitigate appropriately. In this investigation, all sounds are measured at sound pressure levels, which is the level of sound actually experienced at a given location. In terms of received sound, it indicates an average level received by a species. One thing that is hindering progress in the UK regarding noise mitigation techniques for offshore wind turbine installation is legislation making it illegal for any methods of mitigation to be tested on marine mammals in UK waters. It also means that the thresholds of marine mammals living in UK waters is relatively unknown. The thresholds listed in Table 6 are used in the Collaborative Offshore Wind Research Into the Environment (COWRIE) group, which is the official route by which noise mitigation techniques are analysed in the UK (Nehls et al., 2007).

Animal	Temporary Threshold Shift (TTS) dB	Permanent Threshold Shift (PTS) dB
Cetaceans (whales, dolphins, porpoises)	200 peak pressure	230 peak pressure
Pinnipeds (walrus, seals)	204 peak pressure	210 peak pressure
Fish and fish larvae	155	187

Table 6: Temporary and permanent threshold shifts for ocean dwelling species

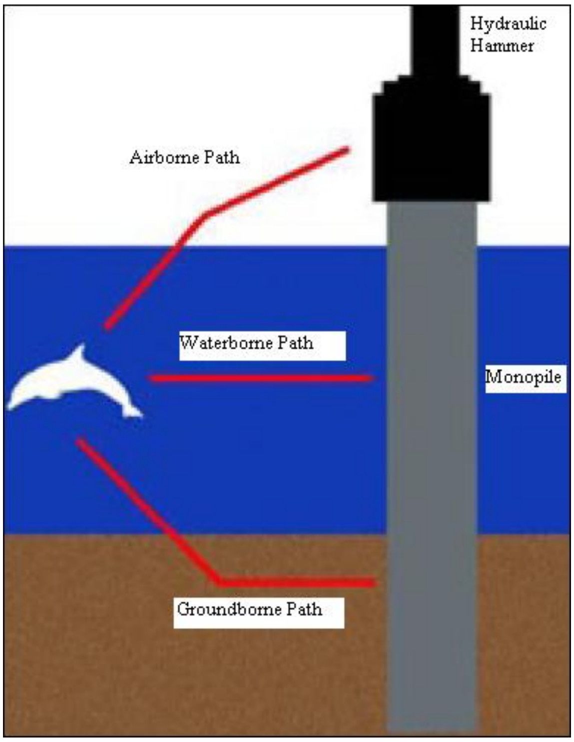

Figure 15: Three different paths for noise travelling away from pile driving (Van den Akker et al., 2012)

Pile driving for both monopile foundations and pin piles for jacket foundations is an installation technique that requires the hammering of the steel cylinders into the seabed. It is a very effective technique however pile driving can cause large amounts of sound to be emitted when the hammer hits the pile and the impact deforms the pile and deflection of the blow disturbs the water (Saleem, 2011). This also leads to sound travelling in the air and through the seabed (Figure 15), and travelling through the water (Figure 16).

Spatial disturbance occurs up to 4km from the noise source, though this is highly dependent on water depth; the rate of sound level pressure decreases with distance as the water gets deeper. However due to the time frame allowed for this project, the change in sound level pressure with depth is not examined here and all noise pressure levels are measured at source at a depth of 30m.

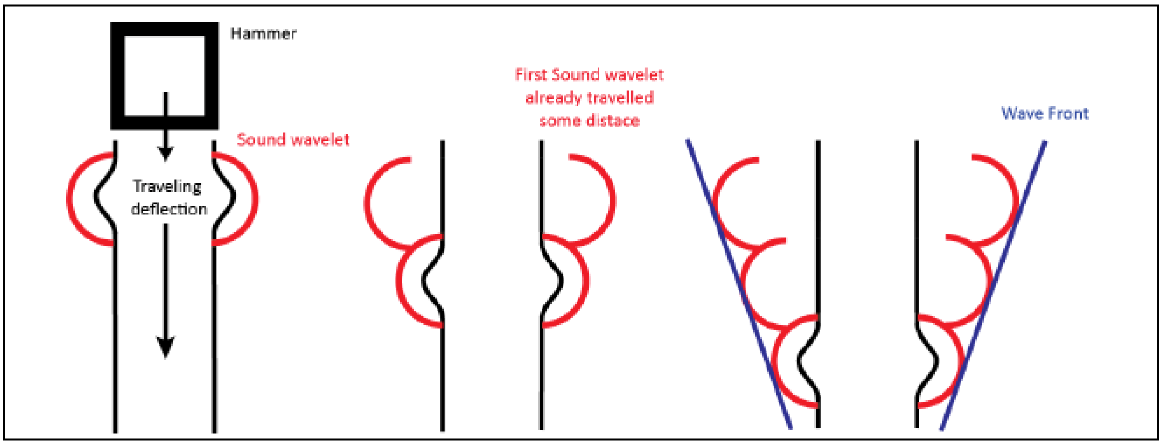

Figure 16: Sound generation during pile driving impact hammer (Saleem, 2011)

Peak levels of pile driving for installation of both mono piles and pin piles for jacket foundations used in this study are listed in Table 7 Although pile driving generally consists of short, sharp bursts of sound as the driver makes contact with the pile/pin which then drives into the seabed, it can take place over a prolonged period of time with peak levels being consistently high. The actual noise from a pile driver is difficult to predict as its dependent on a number of factors including soil type, salinity, sea state, pile diameter, wind speed and power of the hammer (van den Akker et al., 2012)

5.3 Mitigation Techniques

Standard protocol for environmental protection against harm caused by piling noise should include a marine mammal mitigation plan; being able to demonstrate the best available technique with consideration to the local environment based on the "*JNCC Guidelines for Minimising Acoustic Disturbance from Seismic Surveys*" (JNCC, 2004), these include using trained marine mammal observers to be on the lookout for any mammals within a 1km vicinity of the installation vessel which dictates the recommended "mitigation zone", this can also be done in conjunction with passive acoustic monitoring to better detect some species that would not surface within this timeframe. A "soft-start" should be used when the piling begins where there is a gradual ramping up of piling power over a set period of time until full power is achieved (JNCC, 2010), this alerts marine mammals within the immediate vicinity and should theoretically disperse them before the piling operation reaches full power. In many places, a seasonal restriction applies; this is to avoid breeding or migration patterns when there is more likely to be a higher population of certain species within range of the development.

These concerns are only applicable to monopile (Table 7) and jacket foundations (Table 8) where piles have to be driven into the seabed to provide stability, for gravity base foundations (Table 9), the loudest noise received will be that of the vessels on the surface of the sea.

Turbine – Monopile Foundation	Diameter m	Peak Hammer Strike kJ	Average time for installation Hours	No of impacts per monopile	Effective Exposure Source Level dB re 1μPa@1m
Vestas V112-3.0MW	4.9	1297	4	14,000	220
Siemens SWT-3.6-120	6	1050	5	14,000	230
AREVA M5000-135 5MW	6.1	1100	5	14,000	240
REpower 6M	6.9	1500	6	14,000	241
Vestas V164-8.0MW	8.5	3,000	6	14,000	260

Table 7: Peak effective exposure levels for installation of a monopile foundation at 30m depth

Turbine – Jacket Foundation	Diameter m	Peak Hammer Strike kJ	Average time for installation Hours	No of impacts per monopile	Effective Exposure Source Level dB re 1μPa@1m
Vestas V112-3.0MW	1.4	604	<2hrs	12,000	209
Siemens SWT-3.6-120	1.37	604	<2hrs	12,000	217
AREVA M5000-135 5MW	1.8	800	<2hrs	12,000	225
REpower 6M	2.5	900	<2hrs	12,000	279
Vestas V164-8.0MW	3.5	1100	2.5hrs	12,000	240

Table 8: Peak effective exposure levels for installation of a jacket foundation at 30m depth

Turbine – GBS Foundation	Diameter m	Peak Hammer Strike kJ	Average time for installation Hours	No of impacts per monopile	Effective Exposure Source Level dB re 1µPa@1m
Vestas V112-3.0MW	18	N/A	5	N/A	90 (Vessel)
Siemens SWT-3.6-120	22	N/A	5	N/A	90 (Vessel)
AREVA M5000-135 5MW	25	N/A	5	N/A	90 (Vessel)
REpower 6M	28	N/A	5	N/A	90 (Vessel)
Vestas V164-8.0MW	35	N/A	5	N/A	90 (Vessel)

Table 9: Peak effective exposure levels for installation of a gravity base foundation at 30m depth

5.3.1 Acoustic Deterrent Devices

Acoustic Deterrent Devices (ADDs) or pingers are a powerful noise emitting device that can be used to prevent marine mammals from coming into the vicinity of the piling driving area. However some studies have found that these cause pain or discomfort to seals (Gordon et al., 2002), and they are not suitable or effective for all species including some whales, dolphins and porpoises therefore are not a suitable option for deterring marine mammals from pile driving operations.

Alternatively more physical methods can be employed to create a barrier between the noise source and receptors;

5.3.2 Bubble Curtain

A bubble curtain is one such method; bubbles of air are produced by a compressor on board a ship at the surface and air being pumped out of hoses at the seabed before piling begins. After a period of a few minutes, the bubbles have risen to cover the full depth of the water column which breaks the propagation of sound waves as they are emitted from the pile driver connecting with the sea bed, this is possible due to the difference in densities between air and water. Can reduce sound by 10-20dB at the pile driver (Reyff. 2009) and 3 – 5dB 1km distance away (Wursig et al., 2000) which is ideal for avoidance reaction in cetaceans and pinnipeds.

The noise level reductions using an air bubble curtain are displayed below (Table 10 & 11).

Advantages

- Noise reduction of up to 20dB
- Keeps inquisitive fish away from the pile as it is being driven into the seabed, thus also militating against direct physical injury from pile driving.
- Does not interfere with piling techniques and therefore does not affect the pile driving contractor
- Can be used with current installation techniques
- Can be used in depths of up to 30m

Disadvantages

- Cannot be used in rough weather conditions
- Cannot be used in strong currents or rough sea conditions

5.3.3 Pile Sleeve

A physical barrier can be placed around the monopile to create a pile sleeve; these can either be inflatable, telescopic or steel, sometimes there are multiple layers applied within the sleeve that is filled with water or bubbles to further damped sound, and can reduce sound by up to 27dB at the location of the pile driver (Koschinski et al., 2011). The use of the pile sleeve does not require any modifications to the current design of monopiles; however it does require time to install the extra infrastructure and pile installation contractors need to be aware of the process and wait until the sleeve is in place before pile driving can commence.

Advantages

- Noise reduction of up to 27dB
- Can be used in all weathers
- Can be used with current installation techniques

Disadvantages

- Need extra infrastructure
- Increased Installation time

- Extra costs – to cover the longer installation process

5.3.4 Hydro Sound Dampers

Hydro Sound Dampers (HSDs) are a similar concept to bubble curtains; they rely on air bubbles to reduce sound to scatter acoustic wave, however gas filled balloons are used rather than allowing the air bubbles to float freely to the surface, these are attached in a network surrounding the piling. HSD technology is in relative infancy compared with bubble curtains and pile sleeves, however sound reduction of between 10 – 14dB have been recorded (Koschinski et al., 2011).

Advantages

- Noise reduction of up to 14dB
- Can be used with current installation techniques

Disadvantages

- Requires extra infrastructure to constrain the bubbles
- Higher costs due to extra infrastructure and time needed to install this around the foundation
- Can only be used in calm weather conditions

Turbine - Monopile Foundation	Effective Exposure Source Level dB re 1µPa@1m	Bubble Curtain dB re 1µPa@1m	Pile Sleeve dB re 1µPa@1m	Hydro Sound Damper dB re 1µPa@1m
Vestas V112-3.0MW	220	200	193	206
Siemens SWT-3.6-120	230	210	203	216
AREVA M5000-135 5MW	240	220	213	226
REpower 6M	241	221	214	217
Vestas V164-8.0MW	260	240	233	246

Table 10: Peak effective exposure levels for installation of a monopile foundation with mitigation at 30m depth

Turbine - Jacket Foundation	Effective Exposure Source Level dB re 1µPa@1m	Bubble Curtain dB re 1µPa@1m	Pile Sleeve dB re 1µPa@1m	Hydro Sound Damper dB re 1µPa@1m
Vestas V112-3.0MW	209	189	182	195
Siemens SWT-3.6-120	217	197	190	203
AREVA M5000-135 5MW	225	205	198	211
REpower 6M	232	212	205	218
Vestas V164-8.0MW	240	220	213	226

Table 11: Peak effective exposure levels for installation of a jacket foundation with mitigation at 30m depth

5.4 Techno economic

An exact cost for piling sound mitigation is difficult to define as it varies from project to project. It is dependent on water depth, sea conditions and which species are found in the surrounding area.

For each of the techniques, the developer contracts out to a company that can provide a whole package for sound mitigation, entirely separate from the contactor that provides the piling installation. This package includes any additional vessels required; equipment needed and insurance for down time for bad weather days as well as the crew to run the vessels and to operate any machinery.

For bubble curtains the price is more straightforward than for pile sleeves or hydro sound dampers as the price is solely dictated by the contactor as there is no need for any interaction with the piling with regards to pre work required before hammering can begin therefore there is no knock-on effect to the overall project installation time. It is estimated that for this, it will cost €70,000 per foundation.

The use of a pile sleeve is more complex as it requires direct interaction with the pile before installation; this therefore requires extra time to be added on to the project to include any delays that incur. The sleeve is also expensive to manufacture. It is estimated that this will cost €100,000 per foundation

The hydro sound damper is a relatively new technique, but as it is expected to be cheaper to implement than the pile sleeve. It still requires interaction with the pile before hammering can commence, however this is quicker than with a pile sleeve. Costs are estimated to be €85,000 per foundation.

6. Scour

6.1 Scouring

Sediment mobility is a naturally occurring process, normally affected by waves and tides. The presence of manmade objects such as turbine structures can severely influence the mobility of sediments in their immediate neighbourhood. The hydrodynamic field is increased (Whitehouse, 1998), normally resulting in increased sediment transport, known as "scouring" where the seabed is eaten away where the structure meets the seabed. Seabed scour as a result of foundation installation forms a depression in the seabed at the base of the foundation (Figure 17). This has two main concerns for offshore wind developers; firstly the stability of the wind turbine can become compromised as the structure has increased hydraulic loading (DHI Group, 2012), secondly the movement of sediment has a knock-on effect on local habitats, not just with the increased footprint size that is changed due to the presence of the turbine but also smothering beyond the physical footprint of the foundation which is where sediment that has been removed by the increased water flow regime, drops back to the seabed, covering habitats and feeding grounds that were before exposed. Therefore the actual footprint of the foundation for environmental impact must include the overall area of seabed that will change due to the presence of the structure, and the amount of area that will be taken up by scour protection. This can have an effect on one of the main factors that was highlighted in the weighting process undertaken as part of the EES; spawning and nursery grounds, and could therefore lead to a project being denied due to spatial disturbance of the seabed.

Scour is an important consideration as if scour is prevalent in a site, then it could have a large cumulative environmental effect due to smothering and loss of feeding ground

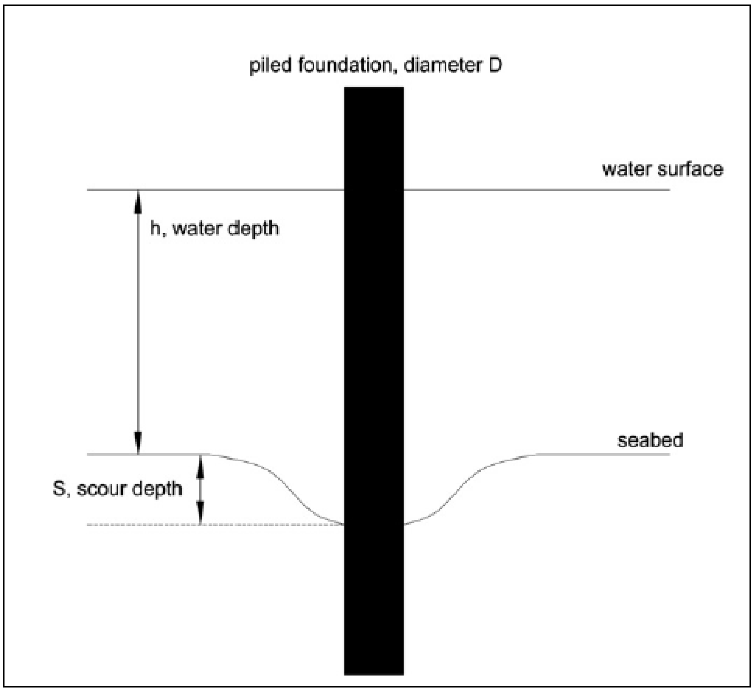

Figure 17: Scour cross section (Whitehouse et al., 2007)

Both the technological and the environmental impacts of scouring have to be taken into consideration at the location of a proposed development and therefore the ability to predict the possible scouring that may occur is of advantage to the developer. The oil and gas industry has extensively examined the effect of scour on the foundations of offshore platforms (Whitehouse et al., 2011) however there is still a high level of uncertainty as to the exact processes taking place, and the use of mitigation techniques that would be suitable for use with offshore wind turbines.

The conceptual model (Figure 18) indicates the time differences between different sediment types and their mobility to be moved during extreme wave periods; scour is predicted to decrease for coarser soils as well as for finer soils where susceptibility to erosion is reduced (Whitehouse et al., 2011) however the assessment of mixtures of material present a challenge due to the spatial, vertical and temporal variation in the soil conditions and this model is therefore based on expert judgement and previous knowledge (Whitehouse et al., 2011).

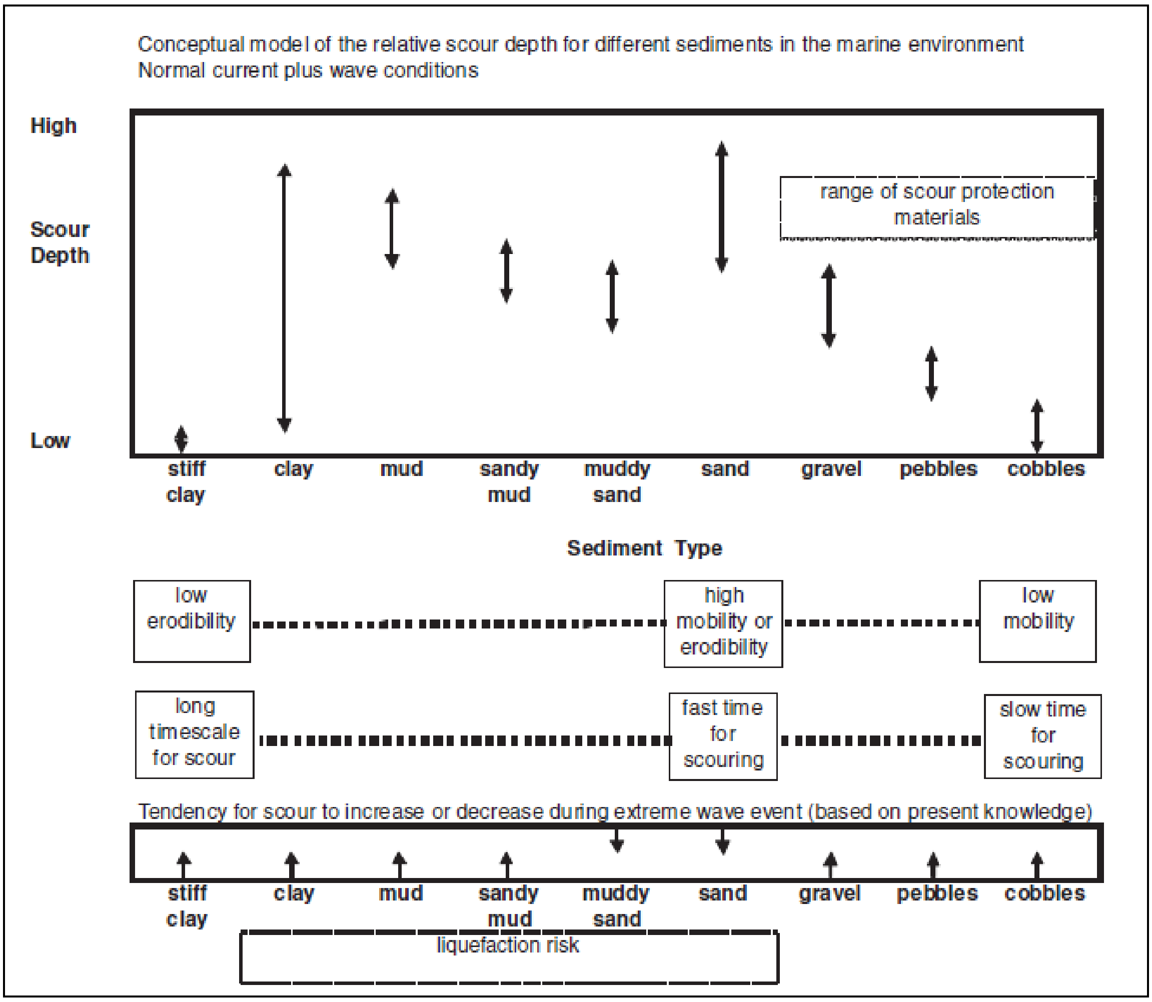

Figure 18: Conceptual model for scour development around marine foundations (Whitehouse et al., 2010)

For example at the East Anglia One site currently under development by Scottish Power Renewables, the seabed mainly consists of sand and the small particles are naturally vary mobile, however at some points on the site, the sediment is much coarser and therefore mobility has to be considered to be different in these areas.

Site characteristics.

Site	Description	Seabed sediment	Monopile diameter (m)	Scour protection	Depth LAT (m)	Mean tide level above LAT (m)	Tide range (n) neap and (s) spring (m)	Peak current speed (m/s)	Annual significant wave height (m)
Scroby Sands OWF	Sand bank, east coast England: exposed to waves, strong currents, fine to medium sand, dynamic sandbank environment, shallow water, presence of mobile bedforms	Medium SAND, some GRAVEL/SHELL, CLAY at depth	4.2	Yes**	3–12	1.6	1.1 (n) 1.9 (s)	1.65	1–3.5****
Arklow Bank OWF	Sand bank, east coast Ireland: exposed to waves, strong currents, sand/gravel, dynamic seabed environment, shallow water	Loose to medium dense SAND and sandy GRAVEL	5	Yes	2–6	1.3	1 (n) 2 (s)	2	5.6****
N7	Open seabed, southern North Sea: exposed to waves, moderate currents, medium sand,dynamic seabed environment, very shallow water	Fine medium dense SAND	6	No	5.2	1.8***	2.6 (mean)	0.75	1.1
Scarweather Sands	Sand bank, Bristol Channel: exposed to waves, strong currents, medium sand, dynamic seabed environment, shallow water	Medium to fine shelly SAND	2.2	No	6	5.4?	4.2 (n) 8.9 (s)	1.1	2.8
Otzumer Balje inlet	Tidal inlet, Wadden Sea: sheltered from waves, strong currents, medium sand, dynamic seabed environment, shallow water	Medium SAND	1.5	No	11.7	1.6	2.6 (mean)	1.4	Sheltered
Destin inlet	Tidal inlet Gulf of Mexico: sheltered from waves, moderate currents, fine sand, dynamic seabed environment, very shallow water	Fine SAND	0.61*	No	3.8	0	0.2 (approx)	0.6	Sheltered
Barrow OWF	Open seabed, northwest coast of England: exposed to waves, moderate currents, sand and clay, stable seabed environment, deep water	Fine SAND to muddy SAND, some GRAVELS overlying CLAY; exposed CLAY	4.75	No	12–18	5.1	4.1 (n) 8.2 (s)	0.8	4.9
Kentish Flats OWF	Open seabed Thames Estuary, England: exposed to waves, moderate currents, sand and clay, stable seabed environment, very shallow water	Fine SAND; infilled paleo-channel with CLAYS and SANDS; CLAY near surface or exposed	5	No	3–5	2.74	2.9 (n) 4.7 (s)	0.9	3.3*****
North Hoyle OWF	Open seabed, north Wales: exposed to waves, moderate currents, gravel/sandy gravel, stable seabed environment, deep water	Gravelly medium SAND or sandy GRAVEL overlying CLAY	4	No	6–12	5.15	4.1 (n) 6.1 (s)	1.17	4.9

* Square pile.
** First survey without scour protection.
*** Mean Sea Level value.
**** Breaking waves.
***** Depth limited at low water levels.

Figure 19: Site characteristics for developments with maximum depth of 18m (Whitehouse, 2011)

The increase in bed shear stress and sediment mobilisation around the foundation of the turbine generally achieves equilibrium over a few tides (Vattenfall, 2011), Therefore using empirical relationships, the equilibrium scour depth for each foundation type can be calculated.

6.2 The Keulegan-Carpenter Number

Turbine foundations present an obstacle on the seabed which leads to flow acceleration due to the convergence of current lines, vortices are generated from the structure increasing the energy of turbulent flows which lead to increased pressure upstream of the obstacle. A first vortex is generated at the seabed by the pressure gradient producing a downward flow. This vortex surrounds the cylindrical foundation and vanishes, whilst producing a second vortex in the shape of a horseshoe

(Whitehouse, 1998). Vortices increase the flow stress upon the seabed and therefore are largely responsible for the appearance of scour.

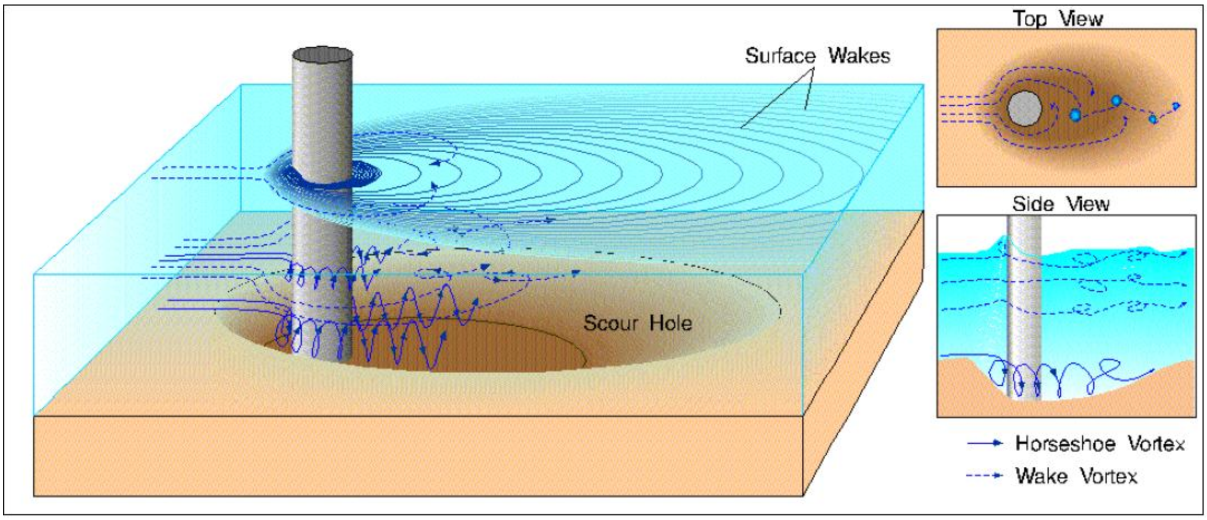

Figure 20: Horseshoe vortex and lee wake (Huizinga et al., 2009)

The Keulegan-Carpenter (KC) number is responsible for producing the horseshoe vortex, however this is dependent on the diameter of the structure and does not appear if the KC is lower than 6 (Figure 21) (Sumer et al., 1992).

Waves also produce scour, however the local change in stress is less than can be seen in current due to a thinner boundary layer and a horseshoe vortex not always being present.

Key parameters that are needed in scour prediction include dimensions of the foundation and environmental data specific to the site; water depth, currents and waves.

Where scour is light is may not be necessary to install scour protection, however where horseshoe vortices are present, they represent the majority of the responsibility for scour around unprotected foundations, as well as the lee-wake (Figure 23). This is unlikely to occur in deep water >30m as waves do not affect the seabed therefore scour is more affected by local currents.

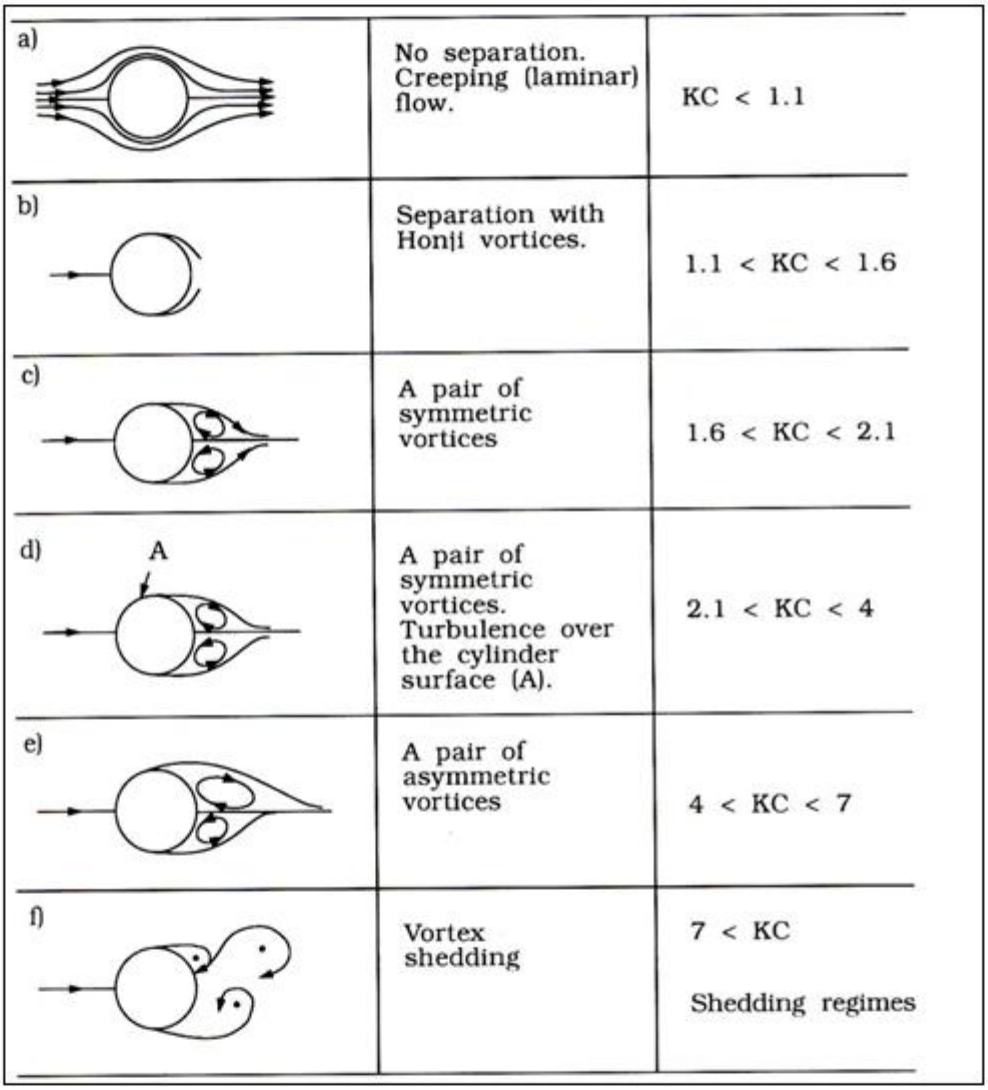

Figure 21: Flow regimes around a smooth circular cylinder for an oscillatory flow. (Sumer et al., 2006)

6.2.1 Global Scour

The scour surrounding the monopiles will be relatively small in diameter compared to the distance between structures within an array, and therefore the effects of turbulence generation between each structure will be negligible therefore the characteristics described here correspond to a single foundation. However, with structures of large diameter such as GBS, or jacket structures, the global scour goes beyond the influence of the foundation and therefore has a large cumulative environmental effect when taking into account the whole array. Therefore a worst-case scenario has to be taken into account where effects on a series of receptors have to be considered; these include sediment transport pathways and seabed morphology. However it is generally accepted that there will be short term changes until equilibrium is reached if the correct precautions are taken into consideration.

Scour around jacket structures are less well documented than those of monopile and gravity foundations as modelling the pins are much more difficult due to their small scale and proximity to each other causing local scour, however their global scour will expand further than the legs of the structure.

6.2.2 Local Scour

Local scour is first analysed by the relationship between diameter of the base of the foundation and water depth. Due to current being the dominating factor in deep waters, a conical scour hole develops first in front of the foundation, then at the sides and finally at the rear. The maximum depth of the hole will be approximately 1.3 – 1.4 of the diameter of the pile. This only applies when the pile is cylindrical (Soulsby, 1997). The extent of scour is approximately 3 times the diameter of the pile upstream, 5 times the diameter downstream. Deposition of sediments removed in the scouring process occurs up to a distance of 8 times the diameter of the foundation (Soulsby, 1997).

6.3 Scour Prediction

There are several models available that try to determine the potential scour depth and scour length at a specific location such as the STEP prediction model concept (Harris et al., 2010) and WiTuS (Dixen, 2012). For the Saint Brieuc and West of Duddon Sands developments, Scottish Power Renewables have referred to the recommendations of the Coastal Engineering Manual (CEM, 2006) of the Coastal

Engineering Research Center of the US Army Corp of Engineers, as it has the advantage of recognising the difference between continuous, unidirectional flow and wave induced flows.

6.3.1 Current Velocity

$$U_{c,sub}(z) = U_{c,sub} \cdot \left(\frac{d+z}{d}\right)^{1/7}$$

Where:

$U_{c,sub}$ = sub surface velocity at the still water level

d = water depth to still water level (taken positive)

z = distance from still water level, positive upwards

6.3.2 Continuous Flow (Colorado State University equation)

$$S_s = 2.0 \cdot K_1 \cdot K_2 \left(\frac{D}{d}\right)^{0.65} \cdot Fr^{0.43} \cdot d$$

With:

D = Pile diameter (m)

$Fr = V_{1m}/(g \cdot d)^{0.5}$ - Froude-number (-)

V_{1m} = Flow velocity 1m above the bottom (m/s)

g = 9.81 - Acceleration due to gravity (m/s^2)

d = water depth (m)

K_1 = Pile shape factor (K_1 = 1 for circular piles)

K_2 = Direction factor (K_2 = 1 for circular piles)

6.3.3 Uniform flow- the Froude number is decisive, for the wave motion the Keulegan-Carpenter number (KC) is the governing parameter

$$KC = \frac{U_{bmax} \cdot T}{D}$$

With:

U_{bmax} = Wave-induced bed velocity (m/s)

T - Wave period (s)

6.3.4 Wave induced Flow

If the KC number above is above 6, horseshoe vortices are present and so characteristics for scour development occur. A vortex due to waves does not appear if the Keulegan-Carpenter number is lower than 6 (Sumer et al., 1992).

The scour depth (*Sw*) is estimated by:

$$Sw = 1.3 \cdot \left[1 - e^{-0.03-(KC-6)}\right] \cdot D$$

6.3.5 Sumer and Fredsøe

Soulsby, (1997) studied the extent of the influence of a superimposed current depth in combination with waves.

The following equations derive an empirical expression for scour depth, S_{wc}, for combined wave and current (Harris et al., 2010).

$$S_{wc=}S_c[1 - exp\{-A(KC - B)\}]$$

Which is applicable when KC ≥B

Where Sc is the depth of scour for the steady-current only case and the parameters A and B are given by the equations:

$A = 0.03 + \frac{3}{4} U_{cw}^{2.6}$

$B = 6\exp(-4.7 U_{cw})$

U_{cw} is the velocity ratio given by;

$$U_{cw} = \frac{u_c}{u_c + u_{0m}}$$

U_c = current speed at a height of Dp/2 above the seabed.

6.3.6 Scour at Foundations

Using the equations described, scour depth was modelled for each of the foundation types; monopile (Table 13), jacket (Table 14) and GBS (Table 15) based on data collected from the ScottishPower Renewables West of Duddon Sands development site.

It was observed that for small diameter monopiles in all depths did not have a significant change in scour depth, however large monopiles made a deeper hole as the water got deeper also.

For jacket foundations, each pin was modelled, again it was observed that for smaller diameter pins, there was not much difference in the scour depth across the different water depths, and for larger pins the hole got deeper as the water depth increased.

However for GBS there is no distinct correlation between water depth and foundation diameter. It is unlikely than any scour hole would reach the depths recorded using this method; a 28m diameter base structure would not make a 36.3m hole in the seabed with a water depth of 15m as the sediment type would stop this from happening - loose sediment would be worn away to just bare rock which would not be eroded in the same way, but these results are in line with Soulsby's (1997) prediction of maximum depth being 1.3-1.4 times the diameter of the foundation. This represents a fundamental flaw with scour prediction; there are many variables within the natural environment that it becomes very difficult to model these empirically in an easily replicable way.

Of course, scour is highly dependent on sea bed sediment type; however for the purposes of this paper, sediment is taken as having a uniform medium cohesion. This is an acceptable industry standard for submission of environmental statements until more investigative techniques are carried out.

Results shown are for scour depth only, this model does not take into account the length of the scour, which can be particularly prevalent downstream from the obstacle.

Turbine - Monopile	Pile Diameter m	Water Depth 15m	Water Depth 20m	Water Depth 25m	Water Depth 30m	Water Depth 35m	Water Depth 40m	Max water depth m
Vestas V112-3.0MW	**4.9**	3.9	4.3	4.4				25
Siemens SWT-3.6-120	**6**	5.4	5.7	5.9				25
AREVA M5000-135 5MW	**6.1**	5.5	5.8	6	6.1			30
REpower 6M	**6.9**	6.6	6.9	7.1	7.2			30
Vestas V164-8.0MW	**8.5**	8.7	9.1	9.3	9.4			30

Table 12: Scour depth using turbines with monopile foundation

Turbine - Jacket	Pin Diameter m	Water Depth 15m	Water Depth 20m	Water Depth 25m	Water Depth 30m	Water Depth 35m	Water Depth 40m	Max water depth m
Vestas V112-3.0MW	**1.4**	0.3	0.3	0.4	0.4	0.4	0.4	49
Siemens SWT-3.6-120	**1.37**	0.2	0.3	0.4	0.4	0.4	0.4	50
AREVA M5000-135 5MW	**1.8**	0.5	0.7	0.7	0.8	0.8	0.8	50
REpower 6M	**2.5**	1.2	1.3	1.4	1.5	1.5	1.5	50
Vestas V164-8.0MW	**3.5**	2.2	2.5	2.6	2.7	2.7	2.7	51

Table 13: Scour depth using turbines with jacket foundation

Turbine - GBS	Diameter m	Water Depth 15m	Water Depth 20m	Water Depth 25m	Water Depth 30m	Water Depth 35m	Water Depth 40m	Max water depth m
Vestas V112-3.0MW 18m	**18**	22.1	22.5	22.7				25
Siemens SWT-3.6-120	**22**	27.8	28.1	28.3	28.4			30
AREVA M5000-135 5MW	**25**	32	32.4	16.9	17.2			30
REpower 6M	**28**	36.3	17.9	18.2	18.5			30
Vestas V164-8.0MW	**35**	46.3	20.7	21.1	21.4	21.6	21.8	30

Table 14: Scour depth using turbines with GBS foundation

6.4 Scour protection

Scour protection is entirely site dependent as the amount of protection required depends on the extent of scour predicted due to sediment type, current and wave interaction and the diameter of the foundation that is in contact with the seabed. Scour protection is available in different formats;

6.4.1 Rubber matting

Rubber matting is a relatively new concept; it consists of a square of rubber put around the base structure to provide a hard surface which will not be affected by the increased flow at the foundation. It is flexible and moulds to contours in the seabed, is simple to install and is easy to remove at the decommissioning stage. However using a rubber mat as scour protection is still in the testing stage of development.

6.4.2 Frond Matting

Frond matting – not industry standard at present but is very adaptable to the sea floor and allows new habitats to grow upon the material, thus creating a natural substance that can be left behind after decommissioning.

6.4.3 Rock Armour

The most common is layering if different types of rock armour – 0.5m of medium grain which is a size of 100 – 200mm, 1.5m of coarse 0.4m, though the thicknesses of these layers can change depending on metocean and geotechnical conditions. Layering is used so that the horseshoe vortex will not penetrate the scour protection and also so that currents will not push aside the smaller material that provides a protection layer between the larger rocks and the seabed. The scour protection footprint is large; covering an area 3 to 5 times the size of the foundation. Estimates for volume of material needed and the area of seabed that will be covered for each of the foundations are listed in tables below.

Turbine - Monopile	Scour Protection Vol at max depth m3	Area of seabed inc scour protection m2
Vestas V112-3.0MW	2100	750
Siemens SWT-3.6-120	2100	895
AREVA M5000-135 5MW	2950	1590
REpower 6M	2750	1960
Vestas V164-8.0MW	3000	2200

Table 15: Scour protection volume and seabed area for monopile foundations

Turbine - Jacket	Scour Protection Vol at max depth m3	Area of seabed inc scour protection m2
Vestas V112-3.0MW	500	365
Siemens SWT-3.6-120	529	372
AREVA M5000-135 5MW	659	1204
REpower 6M	897	1250
Vestas V164-8.0MW	1,359	1433

Table 16: Scour protection volume and seabed area for jacket foundations

Turbine - GBS	Scour Protection Vol at max depth m3	Area of seabed inc scour protection m2
Vestas V112-3.0MW 18m	2,030	3600
Siemens SWT-3.6-120	2,550	4072
AREVA M5000-135 5MW	2,750	6940
REpower 6M	2,897	7540
Vestas V164-8.0MW	3,086	8200

Table 17: Scour protection volume and seabed area for GBS foundations

6.5 Techno-economic

As rock armour is the only type of scour protection that is commercially available, it is the only protection considered here.

Volume of protection required is between 500 – 1500 tonnes per foundation, typically costing €8/ton (personal communication, Geo Technician, Scottish Power Renewables) (Table 18).

Volume of protection required (tonnes)	**500**	**750**	**1000**	**1250**
Cost per foundation(€)	4000	6000	8000	10000

Table 18: Volume of scour protection required and estimated cost

However the cost of the scour protection material is a small percentage of the overall costs; a vessel for material transportation, as well as crew, down time and weather days all have to be included. Here there are a large number of variables to be considered such as vessel size; an expensive larger vessel will require taking fewer trips to shore in order to collect material as it will have a larger holding capacity than a less expensive smaller ship. Developers can generally expect scour protection to be between 10-30% of the total installation costs.

As fatigue and extreme loading occurs when the scour hole is 1.3 times the diameter of the foundation, it may not be economically viable to install scour protection if the scour is very low at a particular site.

Aside from the technical necessities of having an adequate structure to support sliding and bearing capacity, there are also environmental concerns when installing base structures in the marine environments.

6.6 Diversity of habitat at foundation

The introduction of foundations, scour and scour protection sometimes have unintended consequences; the introduction of new substratum on the seabed is likely to increase the diversity of habitat further downstream, and the foundation itself can provide an artificial reef. It has been suggested by Wilson and Eliott (2009) that current designs and techniques for installation of monopile foundations can create a net amount of habitat that is 2.5 times greater than the habitat lost, however it must be borne in mind that the habitat gained will be different to that which was lost due to the nature in which it thrives. Linley et al., (2007), outline potentially enhancing effects of offshore wind structures in Round 2 sites conducted through surveys since construction began in these locations.

Scour and the overall footprint of a foundation if it includes scour protection can have an excessive spatial impact if all turbines in the development were to be taken into consideration, therefore the cumulative impact on the changes occurring on the seabed may be quite substantial.

Installation of scour protection in order to mitigate against undercutting is usually a compromise of engineering and environmental necessity. Having scour protection means that the foundation will ensure that the foundation is safe however it will have a larger overall footprint but the extent might not be as detrimental to the local habitats as scour would be without it. However if the scour depth is not modelled to be as sufficient as to need protection for technical reasons, it is often omitted from the development for economic reasons, at the cost of the environment.

7 Conclusions and Future Work

7.1 Conclusions

There is no single method of objectively analysing all the components of an EIA. Life cycle analysis would seem to provide a solid framework by way of measuring impacts, however it is not so good at measuring effect. For this reason the Environmental Evaluation System was used, allowing a group of experts to attribute weights to each parameter so that impacts and effects can be considered. Using the EES, modelling shows that less turbines are better, which may sound like an obvious conclusion but it demonstrates the need for an improvement in technology so that developments can reach the stated capacity with less machines required to do so. This would decrease the disturbance of the environment through all three phases of development; installation, operation and decommissioning.

However as turbines increase in size, so does the size of the foundation required to support them in order to prevent unnecessary loading to the structure. Two key effects from installing different foundations were identified using the EES and these were linked to installation noise and scour as being the determining factors that could terminate development plans on a cumulative basis.

In the case of large monopiles, the size of the hammer required to install the pile will be too noisy for current mitigation techniques to be effective against many sea dwelling species, therefore there is a requirement for technology to be improved in this area to coincide with increasing turbine size. When considering cumulative impacts, the time taken to install large monopiles could be a limiting factor as the impact would be too large. This would mean that the development consentability could rely on quieter installation methods being required, which is not always possible due to seabed conditions.

Scour could also be detrimental to a project when considered cumulatively; although it is more site specific than sound as it relies largely on seabed conditions, scour needs to be explored as it could present a constraint with regards to choice of foundation. As demonstrated using the model from the US Army Corp of Engineers, scour can occur at all foundation types at all depths and depends on a wide range of factors including depth, current, flow and pile diameter. GBS, although attractive due to the lack of noise disturbance during installation, could present problems due to economic constraints arising from the large volumes of protection material required. Jacket structures are complex when assessing scour, and therefore cumulative impacts are largely unknown. As recognised using the EES, smothering of spawning and nursery grounds could effect on species of conservation interest, and as these are weighted highly within the EIA, any cumulative effect arising from increased footprint size to mitigate against scour is likely to impact greatly upon these environmental receptors.

As more developments are commissioned, lessons will be learnt as to the constraints of the environmental factors concerned, however as the system is so complex, it is highly unlikely that all effects will be mitigated against, indeed many processes may remain unknown. It is important however that mitigation processes improve and the industry drives down the costs of implementing these mitigation techniques so that they are not seen as uneconomical. In cases such as scour protection, the mitigation technique represents a large percentage of the installation costs, and striking the right balance between environmental and economic harmony could be difficult.

It is obvious there is a trade-off between environmental impacts (consentability) and engineering/cost considerations (constructability) that have to be considered. There is a requirement to standardise the process by which these are considered during strategic planning and decision making process thus providing an audit trail and the cause and effects of cumulative impacts can be minimised.

7.2 Future Work

The work undertaken here could be transformed into a working computer model that will consider new and proposed turbines and new and proposed base structures, and show that with different sized arrays, the Rochdale Envelope presented during the planning process can be more defined; areas which are of major concern can be highlighted with the stated limitations being within a more realistic boundary. This would allow alternative designs to be considered on a criteria basis and estimate associated potential impacts and costs and rank them in order of preference, allowing projects to reach maximum energy yield with minimum environmental impact.

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