The potential effects of electromagnetic fields generated by cabling between offshore wind turbines upon elasmobranch fishes

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THE POTENTIAL EFFECTS OF ELECTROMAGNETIC FIELDS GENERATED BY CABLING BETWEEN OFFSHORE WIND TURBINES UPON ELASMOBRANCH FISHES

Research Project

for

Countryside Council for Wales

by

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EXECUTIVE SUMMARY

This report details research supervised by Dr Andrew Gill, at the University of Liverpool, on behalf of the Countryside Council for Wales to assess the potential effects of electromagnetic fields generated by cabling between offshore wind turbines upon Elasmobranch Fishes. The report contains four main sections:

1. A review of the literature relating to electroreception in elasmobranchs and relevant literature on offshore wind farm developments.
2. A review of the current situation regarding offshore wind developments focussing on their environmental impacts with particular implications for British elasmobranches.
3. A summary of the current status and extent of relevant biological knowledge of British elasmobranchs.
4. A pilot study which experimentally demonstrates the response of the benthic elasmobranch, the dogfish *Scyliorhinus canicula,* to two electric fields, one simulating prey and the other the maximum potential output from unburied undersea cables.

Finally, the report provides recommendations for future research considerations.

Project Background

There is currently a move towards the use of renewable energy sources throughout the world, and for those countries with coastlines such as Western Europe, offshore wind power represents a valuable resource.

The installation of offshore wind turbines requires the transport of electricity between turbines and from the turbines to the mainland via submarine cabling which in the process produces electromagnetic fields around the cables. Sharks, skates and rays (subclass Elasmobranchii) have long been known to exploit the electric outputs of organisms in saltwater, to detect and capture their prey. Therefore, there exists the potential for electrosensitive species to detect and respond to the electromagnetic fields produced by offshore power installations.

Research Method

Literature review

The first stage of the project focussed on a literature review of major library databases and Internet based material to provide up to date details on electroreception, particularly by elasmobranches and offshore windfarm electricity generation. During the review published information on British elasmobranch species-specific ecology, biology and conservation status was also collated.

The literature review showed that one of the most widely researched areas is the neurobiology of electroreception. Active electroreception in electric fish has received a lot of attention but only two studies were concerned with active electrolocation by elasmobranchs. The behaviour of elasmobranchs in regard to their electric sense has, to date, been widely neglected.

The potential for offshore wind farms around Europe has been widely discussed, including the potential design for any developments. However, information regarding the electromagnetic fields emanating from underwater power cables used for offshore wind farms is very limited. Environmental Impact Assessments have a limited amount of information on the specifications for undersea cabling and the potential effects of electromagnetic fields on receptive organisms has only been referred to briefly. No published research can be found regarding the effects of electromagnetic fields produced by undersea cables on fish.

Information obtained from the British Wind Energy Association website, CCW, existing installation owners and offshore windpower related companies, both within the UK and Europe, provided supplementary details of the levels of electromagnetic fields potentially emitted by offshore installations. Consultation with the windfarm operators also provided information on the type of cabling and the proposed extent and configuration of the cable network.

Experimental study

The experiment focussed on the collection of observational data from the dogfish *S. canicula,* which was chosen according to the following criteria:

- Dependent on habitats, at some period of their life history, which may be crossed by the planned cabling network.
- Ease of collection of replicable data.
- Availability of species during Jan/Feb 2001

Existing wind power installations are predicted to produce their maximum electric field adjacent to an unburied cable when utilising 150kV cables with a current of 600A. Previous studies have demonstrated that dogfish are attracted towards electric fields created by dipoles passing an 8μA current which simulate prey. Hence the response of dogfish to the maximum predicted electrical fields emitted by an unburied underwater cable could be compared with the effects of electric fields similar in magnitude to those produced by dogfish prey.

An electrical circuit with variable resistance and a salt bridge electrode was constructed to create artificial maximum and prey type electric fields to dogfish in seawater water tanks.

Using standard behavioural techniques the following data were recorded:

- The distance away that the fish reacted to an electric field.
- The attraction or avoidance response, if any, of the fish to an electric field.
- The frequency of attraction or avoidance responses of individual fish over a set period of time.
- The time that the fish remained within a set radius of the electrical stimulus.
- The response of the fish to a control with no current emitted from the equipment.

This preliminary experimental research showed:

1. The benthic shark, *S. canicula,* avoids electric fields at 1000μV/cm which are the maximum predicted to be emitted from 3-core undersea 150kV, 600A cables
2. The avoidance response of the dogfish of 1000μV/cm electric fields was highly variable amongst individuals and had a relatively low probability of occurring in the conditions presented in these experiments

3. The same species individuals were attracted to a current of 8μA (representing an electric field of field of 0.1μV/cm at 10cm from the source), which is consistent with the predicted bioelectric field emitted by prey species.

Conclusions and Recommendations

There is a dearth of objective and definitive published information relating to the question of whether electric fields produced by underwater cables have any effect on electrosensitive species.

The pilot experimental research demonstrated that there is a differential effect in terms of the behavioural response of dogfish to simulated electric fields emitted by prey and those from undersea power cables.

These results, however, should be interpreted from two perspectives in an unbiased and balanced manner. Firstly, in light of the present and future importance placed on renewable energy resources we need to be confident that associated human activity will not be significantly detrimental to a component of the coastal marine ecosystem not previously considered ie. the elasmobranchs. Secondly, we need to be conscious of the real need for alternative energy resources and not use the effects predicted from controlled laboratory investigations to take precedence or unnecessarily influence the prioritisation of renewable energy resource utilisation.

To address these future information requirements there are three areas of work to focus on based on the findings of the present study:

- Further directed biological research, concentrating on species use of the inshore habitats and behavioural responses to electric fields.
- Electric field research, in particular the quantification of fields within different substrata and *in situ* measurement.
- GIS mapping and interrogation, to provide a database, which can guide decisions on the location of offshore windpower sites taking into account potential conflicts with elasmobranchs.

The projects identified and the fact that offshore wind power technology is in its infancy promotes the requirement for substantial support and investment into the development of renewable resource utilisation and its role within the natural ecosystem.

CRYNODEB WEITHREDOL

Mae'r adroddiad yma yn rhoi manylion ymchwil a gafodd ei arolygu gan Dr Andrew Gill ym Mhrifysgol Lerpwl ar ran Cyngor Cefn Gwlad Cymru i asesu effeithiau posibl meysydd electromagnetig wedi'u cynhyrchu trwy geblu rhwng tyrbinau gwynt o'r môr ar y Pysgod Elasmobranciaid. Mae tair prif adran i'r adroddiad:

1. Arolwg o'r llenyddiaeth sy'n ymwneud ag electrodderbyniad mewn elasmobranciaid ynghyd â llenyddiaeth berthnasol ar ddatblygiad ffermydd gwynt o'r môr.
2. Arolwg o'r sefyllfa bresennol ynglyn â datblygiadau ffermydd gwynt o'r môr gan ganolbwyntio ar yr effaith a gânt ar yr amgylchedd ac oblygiadau hynny yn benodol i elasmobranciaid Prydeinig.
3. Crynodeb o statws bresennol ac ehangder y wybodaeth fiolegol berthnasol am elasmobranciaid Prydeinig.
4. Astudiaeth beilot sydd yn dangos ar ffurf arbrawf ymateb yr elasmobranciad dyfnforol, y morgi lleiaf *Scyliorhinus canicula*, i ddau brif faes trydanol, un yn ffugio prae a'r llall yr allgynnyrch mwyaf posibl o geblau tanfor heb eu claddu.

Yn olaf, mae'r adroddiad yn cynnig argymhellion ar gyfer ystyriaethau ymchwil i'r dyfodol.

Cefndir y Prosiect

Mae symudiad ar droed ar hyn o bryd tuag at ddefnyddio ffynonellau ynni adnewyddadwy trwy'r byd ac i'r gwledydd rheini megis gwledydd Gorllewin Ewrop lle y ceir arfordiroedd mae ynni gwynt o'r môr yn adnodd gwerthfawr.

I sefydlu tyrbinau gwynt o'r môr mae angen cludo trydan rhwng tyrbinau ac o'r tyrbinau i'r lan trwy gyfrwng ceblu tanfor sydd yn ystod y broses yn creu meysydd electromagnetig o gwmpas y ceblau. Gwyddir ers tro fod morgwn a morgathod (isddosbarth Elasmobranciaid) yn manteisio ar yr allgynhyrchion trydanol o organebau mewn dwr hallt i ddod o hyd a dal eu prae. Mae yna felly botensial am rywogaeth electrosensitif i ddod o hyd ac ymateb i'r meysydd electromagnetig sy'n cael eu cynhyrchu gan beirianweithiau pwer o'r môr.

Dull yr ymchwil

Arolwg o'r llenyddiaeth

Roedd cam cyntaf y prosiect yn canolbwyntio ar arolwg o lenyddiaeth y prif ddata-basau llyfrgell a deunydd sydd i'w gael ar y Rhyngrwyd er mwyn casglu'r manylion diweddaraf ar electrodderbyniad, yn enwedig gan elasmobranciaid a chynhyrchiad trydan ffermydd gwynt o'r môr. Yn ystod yr arolwg cafodd gwybodaeth sydd wedi'i gyhoeddi ar statws ecoleg, bioleg a chadwraeth y rhywogaeth benodol elasmobranciad Prydeinig hefyd ei goladu.

Roedd yr arolwg o'r llenyddiaeth yn dangos mai un o'r meysydd y ceir mwyaf o ymchwilio iddo yw niwrofioleg electrodderbyniad. Mae electrodderbyniad byw mewn pysgod trydan wedi derbyn llawer o sylw ond dim ond dwy astudiaeth oedd yn ymwneud ag electroleoliad byw gan elasmobranciaid. Hyd yma, mae ymddygiad elasmobranciaid o safbwynt eu synnwyr electrig wedi cael ei esgeuluso yn fawr.

Mae'r posibilrwydd o gael ffermydd gwynt o'r môr o gwmpas Ewrop wedi cael ei drafod yn helaeth, fel y mae'r cynllun posibl ar gyfer unrhyw ddatblygiadau o'r fath. Ychydig iawn o wybodaeth a geir, fodd bynnag, ynglyn â'r meysydd electromagnetig yn deillio o geblau pwer tanfor a ddefnyddir ar gyfer ffermydd gwynt o'r môr. Ychydig iawn o wybodaeth sydd gan Asesiadau Effeithiau Amgylcheddol am y manylion ynglyn â cheblu tanfor a chyfeiriad byr iawn a geir at effeithiau posibl meysydd electromagnetig ar organebau derbyngar. Ni ellir dod o hyd i ymchwil cyhoeddedig ar effeithiau meysydd electromagnetig wedi'u creu gan geblau tanfor ar bysgod.

Trwy gyfrwng gwybodaeth a gafwyd o safle we'r Gymdeithas Ynni Gwynt Brydeinig, gan CCGC, y rhai sydd yn berchen ar beirianweithiau yn barod a chan gwmniau sy'n gysylltiedig ag ynni gwynt o'r môr, o fewn y DU ac yn Ewrop, cafwyd manylion atodol ynglyn â'r lefelau o feysydd electromageteg sydd o bosibl yn cael eu rhyddhau gan beirianweithiau o'r môr. Trwy ymgynghori â'r rhai oedd yn gweithio'r ffermydd gwynt cafwyd gwybodaeth hefyd ar y math o geblu a maint posibl a chyfluniad y rhwydwaith ceblau.

Astudiaeth arbrofol

Canolbwyntiodd yr arbrawf ar gasglu data arsylwadol oddi wrth y morgi lleiaf *S.canicula* a gafodd ei ddewis ar sail y criteria canlynol:

- Dibyniaeth ar ryw adeg o'u bywyd ar gynefinoedd allai gael eu croesi gan y rhwydwaith ceblau sydd wedi'i gynllunio.
- Y ffaith ei bod yn hawdd casglu'r data dyblygiadol.
- Y ffaith fod y rhywogaeth ar gael yn ystod Ion/Chwe 2001

Rhagwelir y bydd peirianweithiau pwer gwynt presennol yn cynhyrchu eu maes trydanol mwyaf y drws nesa i gebl sydd heb ei gladdu pan yn defnyddio ceblau 150kV gyda cherrynt o 600A. Mae astudiaethau blaenorol wedi dangos fod morgwn yn cael eu denu tuag at feysydd trydanol wedi'u creu gan ddeubolau yn gollwng cerrynt 8µA sy'n ffugio prae. Felly gellid cymharu ymateb morgi i'r meysydd trydanol mwyaf y gellir eu rhagweld fydd yn cael eu cynhyrchu gan gebl tanfor heb ei gladdu gydag effeithiau meysydd trydanol tebyg o ran maint i'r rhai a gynhyrchir gan brae morgi.

Cafodd cylchred trydanol gyda rheostat ac electrod pont halen eu hadeiladu i greu'r meysydd trydanol artiffisial mwyaf posibl a'r math fyddai'n denu prae ar gyfer morgwn mewn tanciau dwr wedi'u llenwi â dwr môr.

Gan ddefnyddio technegau ymddygiadol safonol, cafodd y data canlynol ei gofnodi:

- Pellter y pysgod pan ymatebon nhw i faes trydanol.
- Oedd y pysgod yn ymateb, os o gwbl, trwy gael eu denu ynteu'n osgoi maes trydanol.
- Pa mor aml yr oedd pysgod unigol yn ymateb trwy gael eu denu neu'n osgoi maes trydanol dros gyfnod o amser penodol.
- Am faint o amser yr arhosodd y pysgod o fewn radiws set y sbardun trydanol.
- Ymateb y pysgod i reolydd lle nad oedd dim cerrynt yn cael ei ollwng o'r offer.

Dangosodd yr ymchwil arbrofol rhagarweiniol yma fod:

1. Y morgi dyfnforol, *S. canicula,* yn osgoi meysydd trydanol 1000µV/cm sef y mwyaf y rhagwelir gaiff ei ollwng o geblau 3-craidd tanfor 150Kv, 600A.
2. Ymateb y morgi i feysydd trydanol o 1000µV/cm trwy'u hosgoi yn amrywio'n arw o un i un ac roedd yn gymharol anhebygol o ddigwydd dan amodau'r arbrofion hyn.
3. Yr un unigolion o'r rhywogaeth yn cael eu denu at gerrynyt o 8µV/cm (sy'n cynrychioli maes trydanol o 0.1µV/cm 10cm o'r ffynhonnell), sy'n gyson â'r maes bioelectrig a ragwelir y bydd rhywogaethau prae yn ei ryddhau.

Casgliadau ac Argymhellion

Mae prinder gwybodaeth cyhoeddedig gwrthrychol a diffiniol ynglyn â'r cwestiwn a yw meysydd trydanol wedi'u cynhyrchu gan geblau tanfor yn cael unrhyw effaith ar rywogaethau electrosensitif.

Roedd yr ymchwil peilot arbrofol yn dangos fod yna effaith wahaniaethol yn nhermau ymateb ymddygiadol morgi i feysydd electrig efelychiadol yn cael eu rhyddhau gan brae a'r rhai o geblau pwer tanfor.

Dylai'r canlyniadau yma, fodd bynnag, gael eu dehongli o ddau bersbectif mewn ffordd ddiduedd a chytbwys. Yn y lle cyntaf, yng ngoleuni'r pwysigrwydd a osodir ar hyn o bryd ac yn y dyfodol ar adnoddau ynni adnewydadwy mae gofyn inni fod yn hyderus na fydd gweithgaredd dynol perthynol yn gwneud drwg arwyddocaol i ran o'r ecosystem forol arfordirol na chafodd ei hystyried cyn hyn hy. Yr elasmobranciaid. Yn yr ail le, mae gofyn i ni fod yn ymwybodol o'r gwir angen am adnoddau ynni eraill yn lle defnyddio'r effeithiau a ragwelir o astudiaethau labordy wedi'u rheoli i gymryd y blaen neu i ddylanwadu'n ddianghenraid ar y pwysigrwydd o wneud defnydd o adnodd ynni adnewyddadwy.

Er mwyn casglu'r wybodaeth yma y bydd ei hangen yn y dyfodol, mae tri maes y mae angen canolbwyntio arnynt yn seiliedig ar yr hyn gafodd ei ddarganfod yn dilyn yr astudiaeth bresennol:

- Ymchwil biolegol cyfeiriol pellach yn canolbwyntio ar y defnydd y mae rhywogaeth yn ei wneud o gynefinoedd wrth y lan ac i ymatebion ymddygiadol i feysydd trydanol.
- Ymchwil yn ymwneud â maes trydanol, yn arbennig meintoliad meysydd o fewn gwahanol isgaenau ac mewn mesur yn y fan a'r lle.
- Mapio SWDd a holiadau i ddarparu data-bas fydd yn gallu sianelu penderfyniadau ynglyn â lleoliad safleoedd pwer gwynt o'r môr gan gymryd i ystyriaeth y gwrthdaro posibl gydag elasmobranciaid.

Gan fod y prosiectau wedi nodi hynny a'i bod yn ddyddiau cynnar ar dechnoleg pwer gwynt o'r môr mae'n cryfhau'r angen am gefnogaeth a buddsodiad sylweddol i ddatblygiad defnydd o adnodd adnewyddadwy a'i rôl o fewn yr ecosystem naturiol.

CONTENTS

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1. INTRODUCTION

There is currently a move towards the use of renewable energy sources throughout the world, and for those countries with coastlines, offshore wind power represents a valuable resource. The potential of offshore wind is mainly being exploited around Western Europe, mainly by Denmark and the Netherlands[1,2,3]. Britain, however, has the highest wind resource in Europe, but has only one operational offshore wind farm at Blyth, in Northumbria[2,4,5,6]. The introduction of the British Government's Utilities Bill, which places an obligation on electricity suppliers to provide an increasing amount of power from renewable sources, will increase the development of offshore wind power around the British coastline[6,7]. In addition, the recent announcement by the Crown Estate to lease 18 offshore sites to new wind farm developments, subject to award of consent, demonstrates the increasing level of commitment to wind power within the British Isles. The majority of these sites are located along the Irish Sea coast.

The installation of offshore wind turbines will require the transport of electricity between turbines and to the mainland. Modern day technology transports the electricity via submarine cabling which in the process produces electromagnetic fields around the cables. Sharks, skates and rays (subclass Elasmobranchii) have long been known to exploit the electric outputs of organisms in saltwater, to detect and capture their prey, and they are also thought to use the Earth's magnetic field for navigation[8,9]. Therefore, there exists the potential for electrosensitive species to detect and respond to the electromagnetic fields produced by offshore power installations.

Over the past few decades, elasmobranchs globally have suffered dramatic reductions in their numbers due to unregulated fishing and habitat degradation. Life history constraints, such as small numbers of offspring and long maturation periods, mean that elasmobranch populations can not recruit individuals fast enough to replace those lost to fishing and pollution[10]. Nationally, there are a number of anecdotal accounts from the sea fishing industry of rapid declines in stocks of rays particularly along the North Wales coast. Certain species of elasmobranch, such as the common skate *(Dipturus batis)* and the angelshark *(Squatina squatina)*, formerly important fisheries species, are now extirpated from or only occur rarely in Welsh waters and have experienced significant declines all around the British Isles. The status of other commercially important species (for example the thornback ray, *Raja clavata*, other large Rajiids, and the spurdog, *Squalus acanthias*) is of increasing concern for both fisheries and wildlife managers. *S. acanthias* was formerly an important commercial species which has been overfished in Welsh (and European) waters and is now only rarely landed in Wales.

To address this worrying decline in elasmobranch population status a number of initiatives have been put in place for the most affected species. There is now a UK Biodiversity Action Plan (BAP) for the common skate and the basking shark is strictly protected under UK law. Other species are addressed in the UK response to the Biodiversity strategy as species of particular concern[11]. In addition, the Welsh Skate and Ray Initiative is piloting efforts to address declines around the Welsh coast with a view to applying the initiative throughout the UK. Internationally, the Food and Agriculture Organisation (FAO) has an International Plan of Action for the conservation and management of sharks, which covers all Chondrichthyan fishes, adopted by UN states in the late 1990's: to assess threats to shark populations; determine and protect critical habitats; identify and provide special attention, in particular to vulnerable or threatened shark stocks; contribute to the protection of biodiversity and ecosystem structure and function[12].

Therefore, it is imperative to minimise any further threat to Elasmobranchs on both a local and wider scale, and to safeguard the habitats that they currently rely upon to complete their life history.

Offshore developments will be legally required to undertake Environmental and Ecological Impact Assessments to include consideration of the potential effects on all aspects of coastal and marine ecology. Any negative effects of new developments on electrosensitive species, such as the predatory elasmobranchs, could potentially be detrimental to the ecological balance of the local coastal and marine environment. With reliable information on the biology, ecology and behaviour of elasmobranch species in relation to offshore windfarm development we will increase our ability to understand the potential effects upon them.

This report considers the potential effects of electromagnetic field production from undersea cabling associated with wind farms on electrosensitive species. In addition, the report indicates how we may mitigate against any effects based on our current level of understanding.

The report contains four main sections:

1. A review of the literature relating to electroreception in elasmobranchs and relevant literature on offshore wind farm developments.
2. A review of the current situation regarding offshore wind developments focussing on their environmental impacts with particular implications for British elasmobranchs.
3. A summary of the current status and extent of relevant biological knowledge of British elasmobranchs.
4. A pilot study which experimentally demonstrates the response of the benthic elasmobranch, the dogfish *Scyliorhinus canicula*, to two electric fields, one simulating prey and the other the maximum potential output from unburied undersea cables.

Finally, the report provides recommendations for future research considerations.

2. LITERATURE REVIEW

Initially, published and peer review papers were reviewed however the search was extended to web published reports which were considered owing to the relatively recent occurrence of relevant research. The sources of information within each of the categories used in the review are shown in the bibliography.

It has long been known that certain species of fish, such as the electric ray (*Torpedo* sp.), the electric catfish (*Malapterurus* sp.), and the South American eel (*Electrophorus* sp.) can produce electric fields[13]. Although, most organisms are unable to produce electricity voluntarily, they all emit weak electrical currents. These currents are a result of muscle activity, such as respiratory movements, cardiac contractions and locomotion, as well as the electrochemical difference between the animal's internal environment and the surrounding seawater[13,14].

The presence and utility of these electrical fields has been debated for some time, but it is now known that elasmobranchs can detect the electrical fields emitted by themselves and other organisms.

Table 1 describes the results of the literature search on the subjects of electroreception and offshore wind power (see Appendix 1 for details). It shows that one of the most widely researched areas is the neurobiology of electroreception, including the filtering of signals - a total of 20 papers. The behaviour of elasmobranchs with regard to their electric sense has been widely neglected with only seven references concerning passive electroreception in elasmobranchs and a further six regarding other species in a few key papers[8,9,15](Table 1).

Active electroreception in electric fish has been more widely concentrated on with a small number of papers existing. However, only two papers, from a total of 15, concern active electrolocation by rays and skates, which possess either weak electric organs (*Raja* sp.), or much stronger electric organs (*Torpedo* sp.).

The potential for offshore wind farms around Europe has been widely discussed, including the potential design for any developments. However, information regarding the electromagnetic fields emanating from underwater power cables used for offshore wind farms is very limited with only four references available. Relevant Environmental Impact Assessments have a limited amount of information on the specifications for cabling and the potential effects of electromagnetic fields on receptive organisms has only been referred to briefly[16,17]. No published research papers can be found regarding the effects of electromagnetic fields produced by undersea cables on fish.

Subject		**Number of Papers**
Passive electroreception:	Elasmobranchs	7
	Other animals	6
	Total	13
Active electroreception		15
Neurobiology and physiology:	General	15
	Filtering signals	5
	Total	20
Magnetic fields - orientation and navigation		5
Bioelectric fields		2
General - electroreception and elasmobranchs (including books)		16
Offshore wind farm developments and plans		14
Cabling of offshore developments		4
Environmental Impact Assessments		5
Effects of electromagnetic fields on fish		0
Total		94

Table 1. Results of the literature review completed on the subjects of electroreception in elasmobranchs and offshore wind farm developments.

2.1 ELECTRORECEPTION BY ELASMOBRANCHS

2.1.1 *Electric Fields in the Aquatic Environment*

The detection of electrical fields of biotic and abiotic origin is associated with aquatic organisms because of the need for a conductive medium, such as water[18]. Most abiotic fields are DC (direct current) with low frequencies, ranging up to only a few Hertz[18]. These abiotic fields are caused by geological processes and by the Earth's magnetic field and may allow aquatic organisms, particularly fish, to navigate and orientate themselves using them as "landmarks"[8,18]. Phenomena, such as lightning strikes and seismic activity, can also produce high frequency signals, but they probably only constitute unwanted "noise" for electroreceptive fishes[9,18].

AC (alternating current) and DC electrical fields of biotic origin can be of low and high frequency[18]. AC fields emitted due to heart and muscle activity can vary greatly between animals and are generally much smaller than DC fields produced[9,18]. DC fields occur due to biochemical processes which produce millivolt potentials between different parts of the body, and between the animal's body fluids and the surrounding seawater[9,18]. For example, a breathing fish exposes its gill epithelia to the external medium when opening and closing its mouth, and therefore, creates an electrical potential that is above the threshold of detection for many electroreceptive fish[18].

Low frequency electric fields have been demonstrated to exist around many species of aquatic organism, including more than sixty marine vertebrate and invertebrate species, representing nine phyla[18,19,20]. These electrical fields may signal the position, type and physiological condition of an animal and also show a marked increase in wounded organisms[9]. However, the bioelectric fields of marine organisms rapidly decrease in strength with increased distance from the source[18].

High frequency electrical signals are produced by a relatively small number of weakly electric fish (including the rays and skates), which have small electric organs that were considered for a long time to be useless because they do not produce enough current to stun their prey or defend themselves[9,18,20]. Electric organ discharges (EODs) from weakly electric fishes are produced in two forms: brief pulse-type signals and continuous wave-type discharges[9,18]. The EODs of weakly electric fish are used for social communication and active electrolocation[9,18].

2.1.2 *Detection of Electrical Fields*

When an electric field emanating from another organism or inanimate source is detected by a weakly electric or non-electric fish, it is known as "passive electrolocation" or "passive electrorecepetion"[18,21]. In contrast, "active electrolocation" occurs when an electric fish detects distortions in its own electric field (i.e. the EODs it produces) caused by conducting and non-conducting objects in the environment[18,21].

The most commonly encountered form of detecting electric fields is via passive reception of low-frequency voltage gradients which is known to occur in elasmobranches and also catfish, common eels and electric fish of the families Gymnotidae, Mormyridae and Gymnarchidae[9]. Through behavioural experiments the ability of elasmobranchs to detect DC voltage gradients less than 0.01µV/cm - and sometimes as low as 0.005µV/cm - in the frequency range of up to 8Hz, has been demonstrated[18,22,23,24]. This passive reception is achieved using ampullary organs, which only detect low frequency potentials and so can not detect the high frequency electric organ discharge of electric fishes[9].

In contrast, active electrolocation is achieved using high-frequency sensitive, tuberous receptors specifically adapted to detect the current discharged by the electric organs of the electric fish themselves[24,25]. These receptors detect small field distortions associated with objects in the environment, and frequency modulations related to social communication[24].

As passive electroreception is taxonomically predominant and is concerned with any electric field emanating in the environment, the remainder of this review concentrates on the ampullary organs which the Elasmobranchii use to detect electric fields and the subject of passive electrolocation. Both topics are relevant to the potential effects on electrosensory fish of electromagnetic field associated with submarine cabling from offshore wind farms around Britain.

2.1.3 *The Ampullae of Lorenzini*

In 1935, Dijkgraaf demonstrated the ability of elasmobranchs to detect electrical fields when he observed that the dogfish, *S. canicula*, turned rapidly away from a rusty steel wire (placed centimetres from its head) but did not avoid a glass rod until it touched it[12,26]. However, it was not until experiments performed by Lissmann in 1958, and Murray in the 1960s, that the ampullae of Lorenzini (first identified in sharks and rays by Lorenzini in 1678) found in both electric and non-electric fish, were identified as the electroreceptors[26,27,28,29].

The ampullae of Lorenzini, found mainly at the anterior of all elasmobranchs, are variants of the lateral line organs found in all aquatic vertebrate[30]. They respond to mechanical, thermal and chemical stimuli, but the most functional stimulus appears to be electricity[15,27,31]. Murray (1960) recorded electrical stimulation of the ampullae of Lorenzini in various *Rajid* species and in *Scyliorhinus canicula*[32]. Although the rays possess small electric organs in their tails, which can produce pulses of 4V lasting for 0.5 to 1 second - much greater than the threshold for detection - Murray did not consider the ampullae to be used in active electrolocation[20,32]. He suggested that the ampullae were only used for passive electrolocation, due to the similar electrical stimulation of the ampullae of dogfish, which do not possess an electrical organ[32]. This was confirmed in behavioural experiments performed by Dijkgraaf and Kalmijn in the 1960s, using dogfish (and rays), which still responded to electrical stimuli despite the lack of an electrical organ[20,32].

The ampullae of Lorenzini consist of a series of pores on the surface of the skin, leading to canals approximately 1 mm in diameter and up to 20 cm long[13,18,27,29,30]. These canals are filled with a conductive jelly that is composed of a mucopolysaccharide matrix, which has a low resistance similar in magnitude to that of seawater (25 to 30 ohms per cm) [13,18,27,29,30]. The walls of the canals and the fish's skin have a higher resistance, resulting in the canal acting like an electrical cable, connecting the receptor cells with the seawater[18]. The canals, which traverse the dermis and epidermis, terminate in alveoli with ampullary receptor cells situated on their walls[15,27,31]. Electrical fields in the environment of the fish lead to changes in the flux of calcium ions across the membranes of the electroreceptor cells, activating the release of neurotransmitters from the receptor cells which stimulate sensory neurones linked to the hindbrain[14].

In most sharks the pores are evenly distributed between the dorsal and ventral surfaces of the head[34]. However, the dorso-ventrally flattened benthic-feeding rays and skates are unable to use vision for prey consumption because of the dorsal positioning of their eyes and the ventral mouth[33,34,35]. The pore pattern of their ampullary organs is concentrated around the mouth and snout on the ventral surface to permit accurate locating of the mouth onto the prey using bioelectric fields[33,34].

It is known that the number of ampullae and the pore pattern at the body surface are fixed through ontogeny and, therefore, that the spaces between the pores become wider as the animal grows[33]. This means that the ability to detect electrical fields is likely to vary during different ontogenetic phases, although presently little research has been conducted in this area. It has also been noted that the structure of skate ampulla changes with depth[35]. The number of alveoli and the size of the ampulla increase with deeper-dwelling species, suggesting an increased number of receptors[35]. This would perhaps aid prey detection in deeper waters, where prey is scarce and light is diminished[35].

2.1.4 *Filtering Signals*

As a consequence of maintaining their own internal environment, which differs from seawater in its ionic concentration, elasmobranchs produce their own bioelectric fields[36,37,38]. Self-generated fields are associated with ventilatory movements by the fish, which produce DC and AC fields large enough to create electrosensory inputs[36,37,39]. Experiments on freely ventilating animals have demonstrated that electroreceptor afferent nerves respond to electric potentials produced during respiration[36]. It has also been shown that ventilatory stimulation is of a similar amplitude in all the afferent nerve fibres from one ampullary cluster (as well as between different clusters) and can, therefore, be described as "common-mode"[36,37]. Thus, signals of a common-mode nature can be eliminated by a common-mode suppression mechanism that results in the principal electrosensory neurones showing a decreased response to common-mode signals (or ventilatory "noise"), whilst continuing to respond to small, localised dipole electric fields[36,39]. Therefore, elasmobranchs are equipped to respond to the bioelectric fields of their prey without wasting valuable foraging time responding to their own signals.

2.1.5 *The Role of Passive Electrolocation in Prey Detection*

The most common use of passive electroreception is considered to be prey detection, as strongly indicated by the distribution of pores around the mouth and snout of elasmobranchs[36]. Passive electroreception was first described in the catfish, *Ictalurus nebulosus*, in 1917 by Parker and van Heusen, although no specific electroreceptive organs were identified[15,20,40]. They demonstrated that a glass rod placed in an aquarium with a blindfolded catfish, elicited no response until the fish came into contact with the rod directly[15,20]. However, when they placed a metal rod in the aquarium, it evoked a response from a distance of centimetres[15,20]. The fish was observed to either turn towards the rod or away from it, depending on the type of metal it was made from[20].

Parker and van Heusen then simulated the galvanic currents emanating from the rods, by using electrodes placed two centimetres apart and passing a direct current through them[20]. The catfish responded to the electrodes in the same fashion as the rods, avoiding them when currents of 1μA or more were used, and turning towards them when currents of less than 1μA were used[15,20]. Thus, the sensitivity of catfish to electric fields was established.

In 1935, Dijkgraaf noticed the sensitivity of *S. canicula* to a rusty steel wire, which elicited an avoidance response in blindfolded dogfish from centimetres away, whilst a glass rod elicited no response until touched[15,20]. However, it was not until 1971, when Kalmijn performed a series of behavioural experiments, that the significance of the sensitivity of elasmobranchs to electric currents was ascertained[15,20].

Kalmijn demonstrated the importance of electroreception to the feeding response of the dogfish, *S. canicula*, and the ray, *Raja clavata*, to plaice (*Pleuronectes platessa*) which is a natural prey[15,20]. The plaice was covered in sand at the bottom of an aquarium and a few drops of liquefied whiting was injected into the water to motivate the sharks and rays to search for food[15,20]. Kalmijn observed the dogfish making a sudden turn towards the sand-covered plaice when they passed within 15cm[15,20,26].

The dogfish then proceeded to remove the sand above the plaice by sucking it up and expelling it through the gill slits, enabling it to seize the prey in its mouth[15,20,26]. The rays were observed to pounce on the prey, from the same distance, and enclosing it under their body by pressing their pectoral fins to the bottom[15]. The plaice was then dug out using the same "blow and suction" method as the dogfish and devoured whole[15].

To determine exactly which sense *S. canicula* and *R. clavata* used to detect their prey Kalmijn placed a live plaice within an agar chamber and buried it in the sand of the aquarium[15]. Vision was not expected to play a large part in prey detection, as the plaice buried itself in the sand naturally[15]. Thus, Kalmijn wanted to determine the relative importance of the other possible stimuli to the predators - chemical, mechanical and acoustic stimuli - relative to the stimulus of bioelectric fields[15]. The agar chamber let the electrical fields pass through it, whilst impeding the mechanical, acoustic and chemical stimuli created by the plaice[15,20]. When tested, the dogfish and rays still responded in the same way to the plaice (although it was encased in agar) by turning towards it at a distance of 15cm or less[15,20].

Next, the live plaice was replaced by pieces of whiting to determine whether the agar chamber was effective in impeding odour stimuli[20]. The fish showed no response to the food in the agar chamber when they swam over it, but were interested in the odour from the seawater that flowed out of the agar chamber[15,20].

Finally, the impedance of mechanical stimuli by the agar chamber was tested. The agar chamber, which contained a live plaice, was covered with a thin polyethylene film[15,20]. The sharks and rays no longer responded to the prey, although they often passed over it whilst searching for food[15,20]. The attenuation of the mechanical stimulus of the plaice was not considered to be much more from the thin film, than from the agar chamber alone, but the polyethylene film had a high enough resistance to prevent low DC and AC currents to pass through it[15,20]. Therefore, Kalmijn concluded that it was the bioelectric fields of the prey that stimulated the dogfish and the rays to respond[15,20].

Kalmijn then proceeded to test the effect of electrodes placed in the aquarium, to prove that the sharks and rays were attracted to electrical fields. Using salt-bridge electrodes, he discovered that the sharks responded most significantly to weak DC electrical currents of 1 to 5μA, similar to those produced by their prey[15,20]. The predators responded ferociously to the electrical stimuli, digging at the source of the field, until they realised there was nothing edible in the area[15,20]. Kalmijn also discovered that the dogfish and rays were more attracted to electrodes than to a piece of whiting placed nearby[15,20].

Passive electroreception has also been observed in other species of elasmobranch. Dawson *et al* (1980) used field experiments to demonstrate that the smooth dogfish, *Mustelus canis*, responded positively to salt bridge electrodes[8,36,41]. One pair of salt bridge electrodes were placed 2 cm apart and 15 cm from an odour source (simulating a small prey fish), whilst the other pair were placed 5 cm apart and 30 cm from the odour source, to simulate a larger prey item[8,41]. Both electrode pairs emitted an 8μA current and were buried in the oceanic substratum whilst herring chum was used to motivate and attract the sharks[8,41]. A number of attacks were observed from one year-old sharks which aimed at the electrodes 2 cm apart from a distance of 18cm away, giving a total sensitivity of 0.02μV/cm[8,41]. Larger sharks responded to the 5 cm spaced electrodes from 30 cm away, a total sensitivity of 0.01 uV/cm[8,41]. A number of the responses were from at least 38 cm away, which equals a sensitivity of 0.005 μV/cm[8,41]. Young sharks were also noticed to be repelled by the larger-spaced electrodes, suggesting they could discern between electric field intensities and, therefore, between prey types[41].

In another field experiment, Kalmijn also observed blue sharks (*Prionace glauca*) responding to simulated bioelectric currents [8,36]. The odour source and electrodes (emitting a DC current of 8μA) were attached to a horizontal bar which was suspended in the water[8]. Blue sharks were observed to prefer the prey-simulating electrodes, over the odour source or control electrodes[8,36].

Tricas (1982) demonstrated that the "gulp and yawn" feeding behaviour of swell sharks, *Cephaloscyllium ventriosum*, could be induced by artificially produced bioelectric fields[23,36]. For the experiments, Tricas placed a live fish in a plastic chamber with and without an agar lid (to attenuate odour stimulus) and tested the sharks[23]. The sharks were observed to show a "gulp" or "yawn" response under both conditions, and showed no feeding response when presented with the fish in a chamber with a plastic lid, which prevented bioelectric fields being emitted[23]. Therefore, the sharks found the prey using their electric sense and not olfactory cues.

In experiments on the stingray, *Dasyatis sabina*, Blonder and Alevizon (1988) demonstrated that its electric sense was important for prey detection[42]. Electrodes placed in an agar chamber were used to simulate the bioelectric fields of the natural prey of the animal[42]. The stingrays were observed to make well-aimed feeding strikes towards the encased electrodes[42]. Prey items were also concealed in the agar chamber and the rays were seen to strike at the chamber despite the absence of an odour stimulus[42].

The experiments outlined in this review are representative of the current state of knowledge on the behavioural aspects of passive electroreception by elasmobranchs. They demonstrate the ability of sharks, skates and rays to detect their prey using bioelectric fields, regardless of the presence of other stimuli. They also illustrate the ability of elasmobranchs to detect artificially created electric fields of a similar level to those produced by prey items. This is important for the research component of this project, as it relies upon the ability of elasmobranchs to detect their prey using bioelectric fields and, therefore, their potential ability to detect artificial electric fields, including those produced by submarine power cables.

2.1.6 *Active Electrolocation*

"Active electrolocation" is the detection, by electric fish, of their own electrical signals, using their tuberous receptors[18,43,44]. Only a relatively small number of weakly electric fish use their EODs to detect objects with differing electrical properties to that of the surrounding water[43]. These objects cause distortions in the electrical field generated by the EODs produced by the fish[43]. Thus, the current flowing through the epidermal receptors is altered in comparison to the absence of an object[43]. The distortion of the EOD is projected on to the skin surface of the fish, to produce an "electrical image," which varies depending on the object's electrical properties, size, shape and distance from the fish[43,44].

Active electrolocation - first described in *Gymnarchus niloticus*, by Lissmann in the 1950s - can be used by weakly electric fish, including rays and skates, for object location, prey detection, navigation, and social communication, during the day or night[9,18,43,44]. Although active electroreception may be used by a very small number of British rays and skates and has the potential to be affected by electromagnetic fields from submarine cabling, no information appears to exist and like passive electroreception far more research is required.

2.1.7 *Detection of Magnetic Fields by Elasmobranchs*

The electric sense of elasmobranchs is so acute that it can detect electric fields induced by their own swimming and by bulk water movements, through the geomagnetic field of the Earth[45]. These two modes of detection can be used for navigation and are considered to be either:

(a) *passive* - when the animal estimates its drift from the electrical fields produced by the interaction between tidal and wind-driven currents, and the vertical component of the Earth's magnetic field; or

(b) *active* - when the animal derives its magnetic compass heading from the electrical field it generates by its own interaction with the horizontal component of the Earth's magnetic field[43].

There is some evidence of sharks using the Earth's magnetic field to navigate. For example, Kalmijn (1982, 1984) demonstrated that the stingray, *Urolophus halleri*, could be conditioned to find food from an enclosure in the magnetic east and not to visit a similar enclosure in the magnetic west of its habitat[8,46]. Magnetic field intensities matched those of the stingrays' natural habitat, but were produced artificially for the experiments[8,46]. The stingrays were observed to base their choice of enclosure on the direction of the ambient magnetic field, therefore, always returning to magnetic east despite random reversals of the field[46].

Blue sharks, *Prionace glauca*, have been observed migrating off the north-eastern coast of America, and maintaining straight courses for hundreds of kilometres over many days[45]. The only continuously available cue for these sharks to follow is the geomagnetic field of the earth[45]. Scalloped hammerhead sharks, *Sphyrna lewini*, have also been observed to follow the magnetic anomalies along the sea floor of the Californian coast[47].

Thus, it seems probable that elasmobranchs use the Earth's magnetic field to navigate through the oceans, as suggested by Kalmijn[46]. Although this present study was not directly addressed towards the magnetic fields produced by underwater cabling, it should be noted that they might have an effect on navigation by elasmobranchs and possibly other species such as the Cetaceans.

2.2 OFFSHORE WIND FARM DEVELOPMENTS

2.2.1 *Offshore Wind Power in Europe*

The potential for offshore wind development around the coast of Britain is immense and utilisation of this resource has begun recently with the construction of the Blyth offshore wind farm.

The Blyth offshore wind farm is the first of its kind in the UK and is situated off the Northumberland coast[4,5,49]. The project was developed by Blyth Offshore Wind Limited, a consortium comprising of PowerGen Renewables, Shell Renewables, Nuon UK Ltd and AMEC Border Wind[4,5,49]. The offshore development, which consists of two turbines erected one kilometre from the coast and in a water depth of approximately eight metres is close to the existing land-based wind farm on Blyth harbour[4,49]. The two Vestas V66 wind turbines of the offshore wind farm have a capacity of two megawatts, enough electricity to power 3000 average households[4,5,49].

As part of the UK's obligations under the Kyoto agreement, the Government has a target of producing 10% of Britain's electricity via renewable sources by 2010[50]. The Government recently announced that £100 million has been earmarked for the development of solar, wind and wave power sources, which includes offshore wind power[50].

Until April 2001, the proposed sites for offshore wind farms around Britain included Blyth and also Gunfleet Bank and Scorby Sands, both on the South-East coast[2]. However, the Crown Estate have recently provided options to lease certain areas of the seabed to 18 new wind farm developments around the UK[50,51] subject to approval. Currently, these developments will consist of a maximum of 30 turbines[50]. Altogether, one million households could be powered by the new wind farms[50]. The sites for the offshore wind farms, include Redcar, Skegness, Cromer, Clacton-on-Sea, Sheerness, Blackpool, Southport, Liverpool, and Whitehaven in England, and Porthcawl and Rhyl in Wales[50,51]. Owing to the very recent announcement of these plans, the current project was unable to investigate any further details of the developments.

2.2.2 *Power Output*

Wind power turbines produce megawatts of power and their final specifications rely on the amount of power to be produced by the wind farm[1]. An example of the variation possible is the difference between the design for the Blyth offshore wind farm, where two 2 MW turbines were used; and a proposed wind farm at Horns Rev in Denmark, which could consist of a grid of 80 turbines, each with a minimum electrical output of 1.8 MW[17].

2.2.3 *Power Transmission*

The potential effects of electrical connection via cabling of offshore wind turbines to the mainland is the main concern of this report, but it should be noted that underwater power cables already exist, for example, cross-channel High Voltage DC power links, and the recently installed AC cable between England and the Isle-of-Man[53].

Many land-based wind farms now use 33 kV cables, rather than 11 kV cables, owing to their reduced electrical losses and the economy of eliminating the main wind farm transformer used for grid connection[54]. This option is also available for offshore wind farm connection and has the advantage of removing the need for a transformer on site, which would be difficult to maintain[54]. 33 kV cables can link a number of wind turbines together as a network, or "block", which will then require one, three core, 33 kV cable each to transmit the power to shore[54].

Other alternatives include a single 132 kV link to the shore, which has a higher power transmission, but would require an offshore substation for conversion[54]. A High Voltage DC (HVDC) cable link to the shore is another option, which would allow sites to be located further offshore, more power to be transmitted and has less electrical losses than AC, but this option is expensive for distances less than 25 kilometres from shore[16,54,55].

An example of the cabling networks that may be used for larger developments can be seen in the Horns Rev offshore wind farm proposal[17]. The internal network of cables will consist of three core, 33 kV Cross Linked Poly-Ethylene (XLPE) insulated cables[17,56]. XPLE cables have widespread use on land and require an impermeable barrier over their insulation for use underwater[54]. The internal network will be linked to a central platform, which will transform the power in order for it to be transmitted to shore by a three core, 150 kV oil, or XPLE insulated, cable[17,56]. The cables will be buried to a depth of one metre in the seabed, but owing to the dynamic environment at the Horns Rev site, there is a possibility that cables may be exposed at the substratum surface for short periods of time[53]. Hence any electric fields emitted are likely to vary.

The turbines at Blyth, however, have been linked to the shore with 11 kV submarine cables, terminating at a control building at the Port of Blyth[5]. Tunoe Knob, in Denmark, also differs in power transmission, with a 10 kV medium voltage submarine cable connecting 10 Vestas V39 500 kW turbines to the shore[16]. Further offshore developments are expected to increase in size, distance from the shore, and power production (up to 1000 MW) due to the economies of scale, and so, will require connection to the shore via higher voltage lines, therefore, making it necessary to incorporate offshore substations into the developments[1,16,54].

Submarine cables installed for offshore developments will mostly be buried, depending on the properties of the seabed and ecological considerations[52]. Burial will protect cables from damage and prevent them from posing a physical barrier to fishing equipment and anchors[52]. To bury the cables, trenches may be dug prior to cable laying or, alternatively they can be water-jetted or ploughed into the seabed after they have been laid[52]. There will be a protection zone around the wind farm and cables, of 200-500 metres, within which no anchoring or fishing will be permitted[17]. An important question arises concerning the attenuation of the electric field from the cables by different substrata. This is particularly important when considering that many species have specific habitat preferences (including preferred substratum) at different times of their life history. The proposed protection zone could be important as a no take or refuge zone for commercial and bycatch species such as elasmobranchs, and may also provide protection from commercial fisheries for some nursery grounds.

2.2.4 *Electric and Magnetic Fields from Submarine Cables*

The current flow within submarine cables causes magnetic and electric fields around the cables which could have a potential effect on fish and sea mammals[16,57]. The sensitivity threshold of some species appears to be significantly lower than the electromagnetic field level close to a cable, therefore, increasing the opportunity for interference with natural behaviour[57].

Geomagnetic fields are used for navigation by certain species and the production of similar magnetic fields by cables can affect these species and human navigation, too. For example, the Baltic HVDC cable between Sweden and Germany has a 600 MW capacity with currents up to 1330 amps[16]. At a distance of 6 metres from the cable the intensity of the magnetic field is equal to that of the natural geomagnetic field - approximately 50 microtesla[16]. This value is sufficient to cause deviations on shipping compasses at the surface[16].

In theory, the production of magnetic fields can be lowered by using a compensatory effect of "supply and return lines"[16,57]. Two lines with opposite currents laid parallel and close to each other should emit a lower magnetic field than a lone cable, the intensity of which depends upon the distance between the supply and the return line[16]. Thus, a three-conductor cable emits a lower magnetic field than that produced by three single cables, but it also has a more limited transmission capacity[16].

It has also been suggested that the shield and armour of the cable affect the electromagnetic field intensity around it and that a reduction of the field can be achieved by either using copper shield and armour, or by burying the cable[57]. In 1997, Voitovich and Kadamskaya demonstrated that medium voltage cables produce larger electromagnetic field intensities than high voltage cables[57]. The electromagnetic field of a cable is predicted to decrease with an increased voltage class (35 kV to 345 kV) and, therefore, increased current in the core (250 A to 1250 A)[57]. For example, Voitovich and Kadamskaya calculated a decrease in the electromagnetic field from 1235 A/m to 45 A/m for 35 kV to 345 kV cables, with the largest electromagnetic field calculated for the 35 kV cables[57]. Therefore, it is entirely possible for medium voltage cables, which will be the common choice for offshore installations, to have the most pronounced effect on sea fauna[57].

From a personal communication with Eltra, the Danish company who compiled the Horns Rev Environmental Impact Assessment report, the electric and magnetic field intensities of 33kV cables (used for internal networks) and 150 kV cables (used for transmission to shore) were estimated[56]. The 33 kV cables were considered to have a 400A current and the 150 kV cables a 600A current flowing through them for calculations. Owing to the relevance of the Horns Rev project, the electric field intensities predicted from their cable configurations were converted into graphical representations (Figs. 1, 2, 3, and 4). Figures 1-4 show the maximum electrical field around a 33 kV cable and a 150 kV cable, and the dissipation of the field with distance from the cable. This is considered for cables in saltwater with a seabed resistance of 0.7 ohms and also with a seabed resistance of 1.75 ohms, both in a maximum water depth of 25 metres[56]. The information obtained allowed the approximation of the maximum electrical field found around a power cable and therefore, the consequent experimental values.

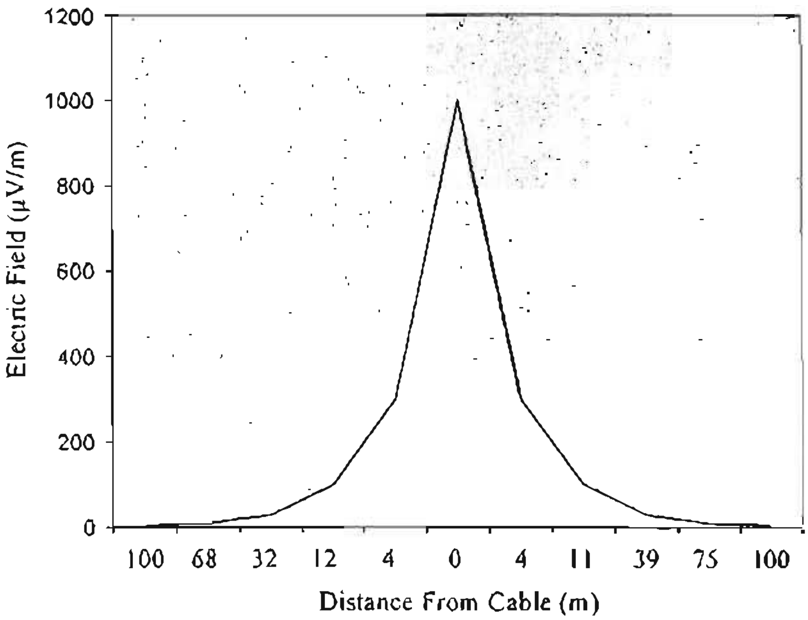

Figure 1. Electric field intensity for a 33 kV cable (400 A current) with a seabed resistance of 0.7 ohms.

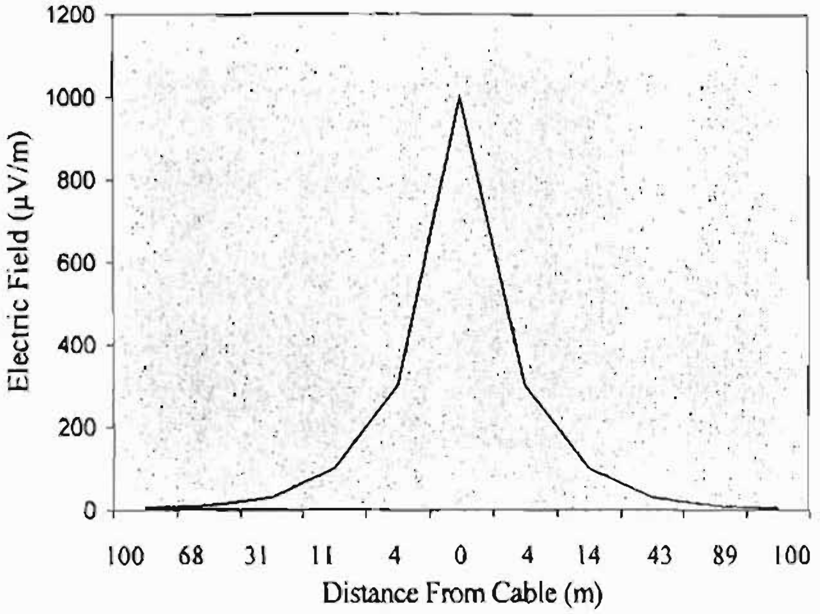

Figure 2. Electric field intensity for a 33 kV cable (400 A current) with a seabed resistance of 1.75 ohms.

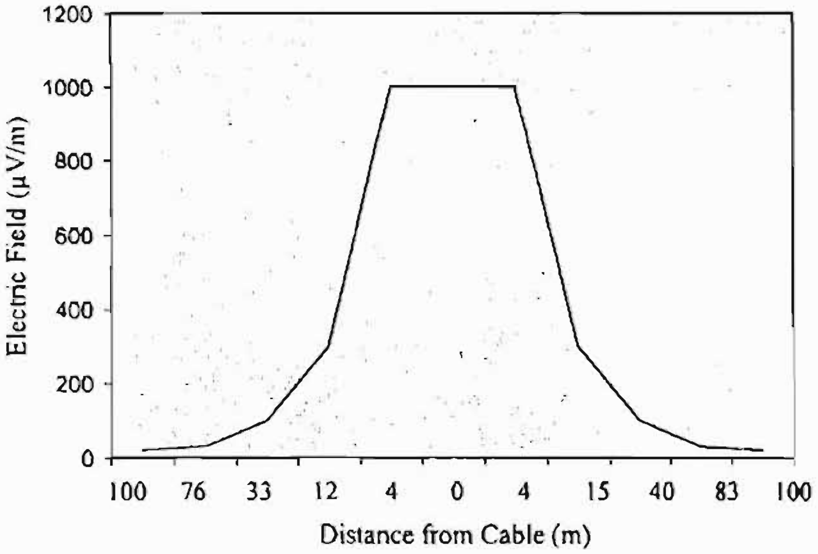

Figure 3. Electric field intensity for a 150 kV cable (600 A current) with a seabed resistance of 0.7 ohms.

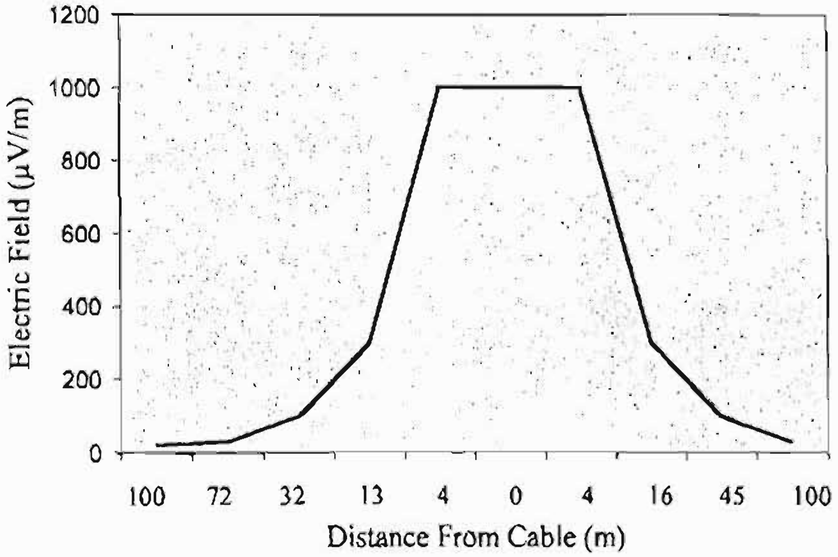

Figure 4. Electric field intensity for a 150 kV cable (600 A current) with a seabed resistance of 1.75 ohms.

2.2.5 *Potential Environmental Impact*

Although the environmental benefits of renewable energy are considerable, the need to assess the potential effects of any development is apparent. Here we concentrate on the effects of offshore developments on the biology and ecology of marine organisms, due to its relevance to the present project. Disturbance to organisms is considered for the two main phases of the life of an offshore wind farm, construction and operation, as the effects of decommissioning the wind farm are considered to be similar to those associated with construction, and so, are only briefly considered.

2.2.5.1 Disturbance during wind farm construction

The seabed will be affected by the construction of the foundations of the turbines, associated substations and by the laying of underwater power cables[16]. Fauna and flora will be disturbed in the area, as sediments are removed and habitats are lost[16,52]. In addition, the turbidity will increase owing to an increase in suspended solids. There is also the possibility of mobilisation of contaminants from the disturbance of the sediments present[16]. After completion of the work, suspended mud and sand will again be deposited over the area[16]. Cable laying will disturb the seabed during construction of the wind farm network, but connection to the grid will only be likely to have an effect on the seabed within a narrow corridor[16]. It is considered that laying the cable may disturb a two metre wide zone on the seabed, but no major impact will occur from this[16]. There is also the possibility of long-term damage from construction, due to permanent changes in the current patterns and the transportation and deposition of sediments around the new structure on the seabed. Hence there are a number of potential effectors on aquatic species, which includes elasmobranches, during the construction phase. The scale of effect is, however, likely to be a function of the species diversity and abundance.

The proposed site for the construction of the Horns Rev offshore wind farm - in the North Sea - is considered to have a sparse fauna, with a low number of species and low numbers of members of those species[17]. Therefore, the impact of foundation construction and water-jetting cables into place will have a minimal effect on fauna and flora, when compared to the natural shifting of the seabed sediments[17]. The total loss of habitat is expected to affect less than 0.1 percent of the benthic fauna at the site[17]. Other proposed sites may have a higher diversity of species, and therefore, construction may have an increased effect on the flora and fauna present. Thus, the construction of a wind farm should take into consideration from the outset the ecological communities present in the area.

Fish (including elasmobranchs) and sea mammals may be disturbed by construction due to the possible disruption of food supplies and the negative effects on less mobile stages of their life cycles (such as eggs and larvae) that may be buried or removed from the seabed[16,52]. Low frequency noise and vibrations from machinery could affect fish, seals, dolphins and whales, to the point where they leave the area[16,52]. Organisms may permanently leave the area if continued disturbance occurs from the turbines, when the wind farm is operation[52]. Finally, the presence of cranes, vessels and eventually wind turbines, may also disturb seabirds by affecting migration patterns, food presence and by causing death[16,52].

2.2.5.2 Disturbance during normal operation of wind farms

Once construction is completed, there is the potential for the foundations to become artificial reefs and support large communities. Evidence for the production of artificial reefs has been documented at the Vindeby offshore wind farm in

Denmark[1,2]. Test fishing was conducted before and after the construction of the wind turbines and the results indicated an increase in fish yields post-construction[1,2]. The turbine foundations at Vindeby act as artificial stone reefs where bivalves and other fauna growing on them attract fish[1,2]. Therefore, it is considered that the flora and fauna at the Vindeby site has increased in diversity since the construction of the wind farm[1,2]. Despite this evidence, it is still a possibility that the benthic communities that colonise the foundations may not be native to the area of the wind farm, and so, may have an impact on the ecosystem[16]. However, due to the ban on commercial fishing around the site of the wind farm, there will be no impact on the benthos from trawling, so fish stocks may increase[16].

Noise and vibrations generated by the operation of the wind turbines may disturb fish and sea mammals in the area. Research on the effects of noise transmitted through water on fish is currently absent in the UK, although at Vindeby fish appeared undisturbed by the noise and accumulated in the area[1,52]. Marine mammals rely on sound to communicate, find prey, and determine the environment around them[52]. Therefore, there is the potential for marine mammals, such as cetaceans, to be affected by noise from wind turbines, but studies at the Vindeby site do not conclude that there is any noticeable change in behaviour or numbers of animals present[2].

Cables transmitting power to the mainland and between turbines have the potential to disturb marine animals that are sensitive to electric and magnetic fields. Electromagnetic fields produced by cables may affect fish, in particular the elasmobranchs and mammals that use the Earth's magnetic field to navigate or for species that may have their social behaviour and communications affected. For example, a magnetic field equal to that of the Earth's, can be detected from the Baltic HVDC cable at distance of 6 metres away[16]. This field can affect ship compasses, and has the potential to effect the navigation and orientation of any animal relying on the Earth's magnetic field in the area[16].

The electric fields emanating from submarine cables may affect species which use electroreception to detect their prey, ie. the elasmobranchs. As demonstrated in section 2.1, sharks, skates and rays use the bioelectric fields of their prey to detect them under conditions, such as low light levels and burial. There is the potential for the electrical fields produced by submarine cables to attract sensitive species at the point where the field intensity approximates the value of their natural prey. Whether, elasmobranchs will be attracted or repelled by stronger fields close to the cable is unknown and forms the basis for the experiment reported in the next section of this project. There is the potential for elasmobranchs to either congregate in the area, or leave it, owing to the presence of electric fields. The latter of these scenarios may particularly cause a problem if the cable runs through an important breeding ground.

There is no research to date on the effects of electric and magnetic fields on sensitive species, yet there is the potential for impact upon them[16]. Therefore, research on the effects of electromagnetic fields on the orientation, migration, and foraging of sensitive species is of importance to Environmental Impact Assessments[16].

2.2.5.3 Disturbance caused by the decommission of wind farms

During decommissioning the power cables will be completely removed from the site and the foundations of the monopiles will be terminated at least three metres beneath the seabed, when the wind farm is decomissioned[16]. The removal of the turbines will also eradicate any potential effects of noise and vibration on sensitive species in the area.

The removal of the cables and the foundations will disturb the seabed in a similar way to when the wind farm was constructed[16]. The seabed above the cables will be disturbed and this will potentially have effects on the benthos. However, the removal of the cables will mean the elimination of any electromagnetic fields in the area, which may have a potential effect on sensitive species, such as elasmobranchs.

2.3 BRITISH ELASMOBRANCHS

The class Elasmobranchii consists of the sharks, skates and rays, all of which have species that inhabit British coastal waters. This section of the report will consider the most relevant species of elasmobranch that may be affected by the electromagnetic fields of submarine power cables, associated with offshore wind farms particularly in Welsh waters. In addition to the electromagnetic fields the geographical location of the wind farms should be considered as many of the elasmobranches have species specific habitat requirements either for feeding or as breeding or nursery grounds.

2.3.1 Sharks

Of the 350+ species of shark worldwide only 21 species are known to inhabit in the continental shelf waters of the British Isles[59]. Although varying greatly in size there are a few features that link all these species, namely an elongated body covered in rough, placoid scale skin with one or two dorsal fins and an asymmetric tail.

The elasmobranchs reproduce through internal fertilisation of a small number of eggs, a strategy which results in a high fertilisation success and protects the developing young. The eggs are either laid externally or they hatch internally and emerge from the mother's uterus into the water. This mode of reproduction differs greatly from most teleost fish (eg. Cod, *Gadus morhua*) which use external fertilisation whereby they introduce tens or hundreds of thousands of eggs and sperm in to the water column, where fertilised eggs have to survive on their own. These distinct differences are extremely important when considering the potential recruitment to populations of fish. The elasmobranchs take much longer than teleost fish to increase numbers owing to the small number of juveniles that are produced and the long period to mature into an adult. Hence, those elasmobranch species that were formerly an important fishery will not be able to recover to population levels sufficient for fishing for some time owing to the constraint of reproductive turnover.

Sharks eat a variety of food types often dependent on their dentary pattern and the habitat that they are adapted to live in, which may be the benthic substratum, mid water or at the surface.

1. The most common shark in British waters all year round is the lesser spotted dogfish, *Scyliorhinus canicula* (also known as the "sandy dog")[56]. They generally feeds on benthic invertebrates and crustaceans, and occasionally on small cephalopods[59,60]. This relatively small species (80cm max length) is reported to be increasing in number possibly as a result of decreased competition from other species which have been reduced through fishing.

2. *Squalus acanthias* (otherwise known as the "spurdog," "piked dogfish," "spiny dogfish," or "common dogfish") is also a common predator of British waters[59]. It can be found off all British coasts, all year round[59]. Again a relatively small species (up to 130cm), which is primarily piscivorous and may hunt in shoals[59]. It is much depleted in European (and Welsh) coastal waters as a result of unregulated exploitation. It has a high commercial value and has a history of boom and bust fisheries.

3. The large spotted dogfish, *Scyliorhinus stellaris* (also known as the "bull huss," or "nurse hound") is less common than its relative, but can be found in the English Channel, the Irish Sea (including Liverpool Bay), and occasionally off the west coast of Scotland[56]. Adults of this species generally grow longer than 100 centimetres[56]. This shark has been known to prey on the smaller *S. canicula*, but generally feeds on cephalopods, crustaceans, molluscs and teleosts[59].

4. *Squatina squatina*, otherwise known as the "monkfish," or "angel shark," is a piscivore found in shallow waters off the British coast all year round where it can attain a size of 180cm[59]. It is most common off the west coasts of Scotland, Ireland, England and Wales, but it is rare in the North Sea[59]. This formerly common species has declined significantly and is now on the IUCN Red List assessment.

5. The "Smoothhound," *Mustelus mustelus*, is not as common off the British coast as its relative *Mustelus asterias*, but can be found in shallow water in the English Channel, the Irish Sea (including Liverpool Bay) and very rarely in the North Sea[59]. This species preys on a mix of benthic invertebrates, including crustaceans, and is generally between 120 and 135 centimetres when fully mature[59].

6. *Mustelus asterias*, also known as the "starry smoothhound," or "stellate smoothhound," is common around the British Isles, except off the coast of west Scotland[56]. It grows to around 130cm and preys on benthic invertebrates, using plate-like teeth specifically for crushing crustaceans and molluscs[59].

7. Larger sharks frequenting British waters include the tope (*Galeorhinus galeus*) which can attain lengths up to 175cm. This species uses inshore areas for pupping and nursery grounds and is a UK Biodiversity 'species of concern'.

8. One of the most famous inhabitants of British waters, the second largest shark in the world, is the 700+cm "basking shark" (*Cetorhinus maximus*)[59]. It can be found in the surface waters off all coasts of the British Isles in the summer months, but is especially prevalent in the Irish Sea and off the Cornish coast[59]. The basking shark is legally protected and has an IUCN Red list status of vulnerable.

9. *Lamna nasus*, otherwise known as the "porbeagle shark," or the "mackerel shark," can be found in British coastal waters all year round[59]. This species eats mainly teleosts and cephalopods and can grow to 300cm in length[59]. This is a very valuable species commercially and recreationally. There is a history of boom and bust fisheries but there remains an important fishery species in Welsh waters. There may be important nursery grounds in the Bristol Channel. The IUCN status is the NE Atlantic population is more threatened than global population.

2.3.2 Skates and rays

There are three main groups of these fish which are related to sharks: the Rajiids, stingrays and the electric rays all of which have a dorso-ventrally flattened body. In Britain, species with long snouts are usually called skates, whilst rays are considered to have shorter snouts[61]. Generally, skates and rays are benthic feeders, eating organisms such as small fish, molluscs, crustaceans and worms[60]. Like the sharks, they utilise internal fertilisation and either produce eggs which are laid externally or give birth to live young. Many species have habitat specific requirements often during the juvenile phase of life. These shallow coastal habitats such as sandy substratum are also preferred sites for the burial of underwater power cables.

Skates and rays are a highly valued catch for commercial and recreational fishermen. The largest species are the most valuable and consequently vulnerable to commercial extinction whilst smaller and more fecund species appear to be increasing[62]. However, there is a lack of species-specific data recording and a lack of catch per unit effort data.

1. The "common skate," *Dipturus batis*, is the largest skate in British waters. It is particularly vulnerable to overfishing, as males mature slowly at around 10 years of age at a size of 125cm, females mature even later producing only 40 eggs per year[61]. Their longevity is estimated at 50 years and they reach a maximum recorded length of 285cm (♀) and 205cm (♂). The common skate was one of the most abundant skates, but it was seriously overfished in Welsh waters and is now extinct off the Welsh and English coasts, being found only occasionally in Scotland and Ireland[61]. It is a BAP species. The IUCN status of this species is Endangered on a global scale (but Critically Endangered for inshore populations. It inhabits all substrata in coastal waters to 600m, favouring the 200m range.

2. The "thornback ray" (*Raja clavata)* is common in all British waters, most of the year, but is seriously declining off the Welsh coast due to overfishing, especially in the case of juveniles[61]. It grows to approximately 65 to 75 centimetres long, maturing at 9-12 years old with the females laying 50-100 eggs per year[60,61]. It inhabitats inshore muddy, sandy and gravel bottoms around 10-16m.

3. The "cuckoo ray," *Leucoraja naevus*, can be found all around Britain, but is more common in the Irish Sea, than in the North Sea[61]. It is found on all types of substrata at 20-250m.

4. The "shagreen ray" (*Leucoraja fullonica*) is an offshore species that can occasionally be found in Welsh waters[61]. This species inhabit rough bottoms at 30-550m.

5. The "blonde ray," *Raja brachyura*, is a large ray, inhabiting most coastal waters, and is a popular target for sport fishing[61]. It prefers sandy and gravely banks at

depths around 40m.

6. *Raja microocellata*, otherwise known as the "small-eyed ray," is a frequent visitor to the coastal waters of South Wales[61]. It lives in shallow water to 100m, favouring sandy bottoms.

7. The "undulate ray," *Raja undulata*, is a species more common to the South of Britain (especially the English Channel), but can be found off the Welsh coast occasionally[61]. It can grow to 100cm in length in British waters[60] and inhabits inshore sandy bottoms at 45-110m.

8. *Raja montagui* (the "spotted ray") is abundant around the Welsh coast, possibly due to the decline of other, larger species of skate and ray[61]. These smaller rays, however, are less valuable for commercial fishermen and for anglers[61]. It inhabits inshore waters to 100m.

9. The "common stingray," *Dasyatis pastinaca*, occurs off southern British coasts in the summer [61]. It has a slender, whip-like tail, with a serrated spine - the "sting" - connected to poison glands, used for prey capture and defence[60,61]. This is a British example of a group that is generally found in tropical waters[60,61]. They give birth to 6 to 9 live young (as do electric rays), unlike other skates and rays which lay egg cases on the seafloor[61]. They inhabit soft sand or mud bottoms in 2-40m, favouring sheltered estuaries.

10. "Electric rays," are related to the true rays and skates (Rajidae), but are members of the family Torpedinidae[60]. Like the stingray these rays are uncommon in British waters. Two species of electric rays have been recorded in Welsh waters, the "electric ray," *Torpedo nobiliana*, and the "marbled electric ray," *Torpedo marmorata*[60,61], where they inhabit sand or mud at a depth of 3-70m.

All the above shark, skate and ray species frequent British waters, including the Welsh coast, and they are all electrosensitive species. Evidence of the use of electroreception for prey detection or navigation may be lacking in certain species, but all species possess electroreceptors and, therefore, have the potential to be affected by electromagnetic fields emanating from underwater power cables. This potential has been further investigated by the experiment reported in the next section (3.0) using simulated bioelectric fields and electric field intensities similar to those emanating from submarine power cabling.

3. EXPERIMENTAL STUDY OF THE POTENTIAL EFFECTS OF CABLING ON ELECTRORECEPTION IN ELASMOBRANCHS

Note: The original aim was to study the electroreceptive behaviour of the Thornback ray (Raja clavata) owing to its benthic lifestyle and commercial and recreational importance around the Welsh coast, however, the timing of the study prevented easy collection of this species, which only moves inshore in the spring.

3.1 Introduction

The experimental study was undertaken to determine if there were any potential effects on the electroreceptive behaviour of elasmobranchs encountering electric fields similar in magnitude to those that would be produced by cabling from offshore wind farms. Existing wind power installations produce the maximum electric field adjacent to an unburied cable when utilising 150kV cables with a current of 600A[56]. Previous studies have demonstrated that dogfish are attracted towards electric fields created by dipoles passing an 8μA current which simulate prey[15,63]. Hence the potential effects of the maximum predicted electrical fields emitted by an unburied underwater cable could be compared with the effects of electric fields similar in magnitude to those produced by dogfish prey.

3.2 Aim of the Study

The central aim was to compare and contrast the behavioural response of dogfish when presented with two artificially created electric fields, one simulating the electric field of a prey item and the other the field associated with a power transmission cable of standard specification.

3.3 Methods

3.3.1 *Study Species*

Lesser spotted dogfish, *S. canicula* (hereafter referred to as 'dogfish'), were obtained by trawl fishing by the University Research Vessel Roagan in the near shore waters around the University of Liverpool Port Erin Marine Biological Station, Isle of Man during February 2001.

Although a benthic species, the dogfish is a small, slender shark with a tapering body and a rounded snout[60]. There is, therefore, a basic morphological difference between the dorso-ventrally flattened rays and the dogfish, which results in electroreceptive pores being spaced over a smaller surface area at the anterior of the dogfish, which may have consequences for species specific electrosensitivity. Other studies have demonstrated interspecific differences in response within the Rajidae and between the Rajidae and Scyliorhinidae[63,65].

3.3.2 Experimental Equipment

Three 1.5m diameter black, acrylic tanks with a water depth of 75cm were set up with a flow through system of water fed directly from Port Erin Bay. 24 adult dogfish, estimated at 65cm total length, were distributed between the tanks.

To produce electric fields in the experimental tanks an electric circuit was constructed consisting of a 9v battery power source, a variable resistor, a multimeter to record the electric current and a set of cables terminating in two electrodes set within plastic aquarium tubing to form a salt bridge. To simulate the electric field of a prey we used a current of 8μA, which was recorded by the multimeter.

Electric fields emanating from a 150kV electric cable with a 600A current were predicted from finite element numerical analysis based on Maxwell's equations for electric fields and their mutual coupling, kindly provided by S.D. Mikkelson[56]. To produce the predicted maximum field of 1000μV/m, we first determined the distance from the electrodes that a field of this strength would reliably be located following the mathematical rationale and equation used by Kalmijn[8] (again derived from Maxwell's equations). From the equation we then predicted the current required. With a power source measured at 8.2V and a predicted current of 6.8A we calculated, according to Ohm's Law, that the circuit required a 1.2ohm resistor. Owing to the resistance of the multimeter available we were not able to measure the current expected during the experiment without altering the electric field significantly, we therefore took the meter out of the circuit.

The salt bridge electrode cabling was held within a plastic piping framework, which was haphazardly placed on the bottom at a distance of 60cm from the centre of the tank. The openings of the salt bridge electrode lay on the base of the tank, which had a thin covering of sand. An aquarium piping circle of 10cm radius was attached with the electrodes at the centre. This circle was used as a visual reference point to indicate the location of the maximum predicted electric field. In addition, the plastic pipe framework that lay across the base of the tank was marked off at 5cm intervals to provide a visual estimate of distance away from the electrode that the sharks responded.

The dogfish encountered three experimental treatments:

- 8μA electric field
- Max predicted electric field
- Control - using all the equipment but without a power connection.

The tanks were visually isolated by a surrounding barrier of black plastic to prevent any disturbance from outside the tanks. The experimental observer remained stationary at the side of the tank during each sample period.

3.3.3 Behavioural Observations

3.3.3.1 Pilot phase

Prior to the experiments we conducted pilot observations to determine a suite of quantifiable, unambiguous behaviours which could measure whether the sharks responded differentially to the experimental treatments. During the pilot phase we noted an increase in movement of the dogfish when food, queen scallop flesh *(Aequipecten opercularis)*, was available. Such induced movement became necessary to increase the probability that the dogfish would encounter the experimental apparatus. Sharks are well know to use a hierarchical sense response with olfaction predominating at a distance and electroreception taking a major role in the final 20-30cm of a reaction to a stimulus source[66]. We therefore introduced 30ml of liquid, obtained from macerated scallop, into the water during the experiments to induce movement and recorded the time to the first movement response of the dogfish.

3.3.3.2 Temperature considerations

The response of the dogfish to the scallop scent was relatively low, possibly due to low motivation as a result of recent feeding and/or slow metabolism in response to the low temperature of the water. Studies undertaken at The Blue Planet Aquarium, Ellesmere Port, have demonstrated a high proportion of response to mollusc scent by Scyliorhinid dogfish at temperatures of 12°C+ [63]. We therefore factored in an increase in temperature to one of the tanks, however, owing to logistical constraints and available time we were only able to raise the water temperature by approximately 3°C. This temperature differential has been considered in our analyses (see section 3.4.2). During the experiments we did not feed the dogfish to standardise motivation between individuals and to increase the potential for response as previously shown by Kalminjn[15].

We were able to unambiguously define the following variables by observing the dogfish:

1. Response to scent introduction per number of fish in each tank and therefore each temperature
2. Response in/out of 10cm radius circle + time spent within circle
3. 3-D position within tank in relation to circle
    - At the surface
    - In the water column
    - On the bottom of the tank
4. Positive reaction towards the electrodes
5. Avoidance reaction to the electrodes + the avoidance distance

3.3.4 Experimental Design

In the project proposal some of the experiments were outlined to use different depths of substratum. Subsequent to the pilot phase the study was altered to determine if there was a behavioural difference between a known electric field attractant and an electric field predicted to be associated with electric cabling at maximum strength. Considering the time period available the depth experiment was omitted to include the new experiment.

Each experiment consisted of a 15 minute equipment adjustment phase, a 15 minute experiment with the water circulation turned off, a 30 minute rest phase with the water circulation turned on to remove the previously introduced scent followed by the next treatment in the sequence of three (Table 2). One of the three sequences was randomly presented to the dogfish in a tank to reduce potential learning and sequential effects between each experiment.

Experiments were conducted over the period 7/3/2001 to 16/3/2001.

Treatment order			
First	Second	Third	No. of experiments
Ctrl	8μA	Max	4
8μA	Max	Ctrl	5
Max	Ctrl	8μA	5

Table 2. Three sequences of the experimental treatments.

The number of experiments conducted for each sequence of treatments (Table 2) was limited by logistical problems and the time allotted to the project. The mean temperature (±S.D.) in tanks 1 and 3 was 7.2 (±0.2)°C whilst in tank 2 the temperature was raised to 9.1 (±0.9)°C.

3.3.5 Analyses

Frequency data were converted into proportions based on the number of individuals that responded. These proportions were then arcsine transformed to normalise the results before ANOVA. Ordinal data were analysed by ANOVA without transformation. All data were analysed using the Statistica software package.

3.3.6 Detection of Electric Fields in situ

In the original proposal electric fields emitted by a simulated cable set up at different depths were to be measured. Although this was deemed possible in principle, subsequent construction and testing of an appropriate electrometer by the Electrical Engineering Electronics workshop was hampered owing to the sensitivity of measurement required. Owing to project time constraints we were unable to fulfil this component of the work.

3.3.7 Animal Welfare Considerations

The principal investigator is a Home Office approved licence holder within the field of animal behaviour and conducted the experiments in accordance with Guidelines laid down by the Association for the Study of Animal Behaviour. Although the experiments undertaken did not appear to harm or distress the dogfish it is important to establish an approved protocol to ensure that any welfare issues do not arise. This aspect of the work needs careful consideration in future projects.

Following the experiments the dogfish were killed according to Schedule 1, Home Office Licencing procedures. These fish will subsequently be used in anatomical training programmes.

3.4 Results of Research

3.4.1 Dogfish Response

A response was recorded when the fish were induced to move following the introduction of fish scent. A response always resulted in entry into the 10cm circle (Table 3) except during the Max treatment where the fish would sometimes avoid the area of the circle (see section 3.4.4).

The time of first response did not differ between treatments beginning at a mean of 2.3 (±2.9 S.D.) minutes after the scent was introduced (ANOVA $F_{2,40}$=0.64, p<0.53) . The overall duration of response of 9.9 (±3.9 S.D.) minutes within the 15 minute experimental observational period was not significantly different between treatments, (ANOVA $F_{2,40}$=0.56, p<0.58).

Of the 24 dogfish that were the subjects of study we found significant individual variability in response. We attempted a tagging procedure on some individuals but the disturbance to the animals was considered to be unnecessary considering the scope of the project. Therefore, we recorded the number of fish responding per 15 minute experimental treatment. The maximum and minimum number of individual fish in a tank which responded during an experiment was similar for all the treatments (Table 3). This is an important result demonstrating that not all the fish respond in a similar manner to an olfactory stimulus and subsequently encounter an electric field.

	Treatment		
# Dogfish	**8µA**	**Max**	**Ctrl**
Maximum	5	6	6
Minimum	1	1	2
% responses within circle	100	75	100

Table 3. The maximum and minimum number of individual dogfish responding in any one experimental observation period.

3.4.2 Effect of Temperature

In an attempt to increase the number of responses by the fish the water temperature of one of the tanks was increased. The number of responses by the fish per treatment at high (9.1±0.9°C) and low (7.2±0.2°C) temperature was not significantly different (t-test: 8µA t=-0.724, d.f.=13, p=0.48; Max t=-1.063, d.f.=13, p=0.31; t=-0.52, d.f.=11, p=0.61).

Of those fish responding we were able to further subdivide their behaviour in relation to the experimental apparatus.

3.4.3 Positive Reaction to the Electrode

When a dogfish approached the electrode we recorded their behaviour. Only for 2% of the responses did we observe a positive attraction to the electrodes. This result needs to be considered in the context of the electric field produced by an 8µA current and the depth of the water. Dogfish are able to detect this field at a maximum distance of approximately 25cm[8], hence there was a large volume of the tank where they would not have encountered the electric field present. Notwithstanding the low activity of the fish and individual variability that existed, a highly significant percentage of the positive reactions (94%) occurred when the 8μA current was encountered (Fig. 5; χ^2 = 22.31, d.f.=5, p<0.0005).

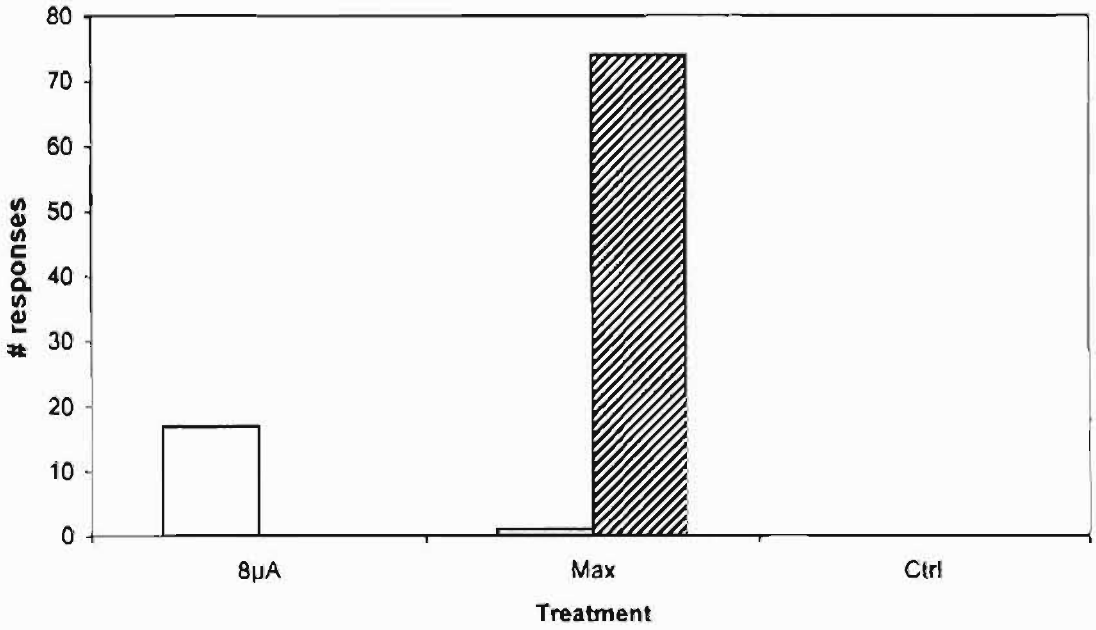

Figure 5. The number of positive (☐) and avoidance (▨) reactions of dogfish in relation to experimental treatment.

3.4.4 Avoidance response

Owing to constraints linked to the experimental set up we set the maximum electric field at 10cm from the electrodes. Hence, if the fish responded it was likely that they would react to the electrodes outside of the circle. We therefore recorded data both within and outside the circle. This alteration to the data recording procedure was a result of the obvious change in behaviour of the fish when nearing the circle. An avoidance reaction occurred when the fish markedly deviated from their forward swimming path away from the circle and the electrodes. 8% of the reactions recorded were avoidance behaviour. All of these reactions occurred during the Max treatment (Fig. 5; χ^2=206.15, d.f.=5, p<0.000001) with a mean distance of avoidance = 10.4cm (±8.2 S.D.).

3.4.5 Depth related behaviour

Electric fields generated by an electric dipole spread out in the water column as an inverse cubic function of the axial distance from the dipole if all other parameters are kept constant[8]. We, therefore, subdivided the behavioural response of the fish by position within the water. Table 5 and Figure 6 show the three spatial categories that were used by the fish. The fish passed directly above the circle at the surface significantly more during the Max treatment than the 8µA (Table 5, Fig. 6; ANOVA F=3.35, d.f.=2, p=0.045; Tukey post-hoc p=0.042).

	Treatment					
	8µA		Max		Ctrl	
Spatial position	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
At surface	0.08	0.14	0.27	0.27	0.15	0.17
Water column	0.26	0.22	0.40	0.34	0.31	0.19
Tank Bottom	0.66	0.26	0.33	0.32	0.55	0.21

Table 5. Spatial position in the water in relation to the 10cm radius circle around the electrodes, shown as mean (±S.D.) proportions for each treatment.

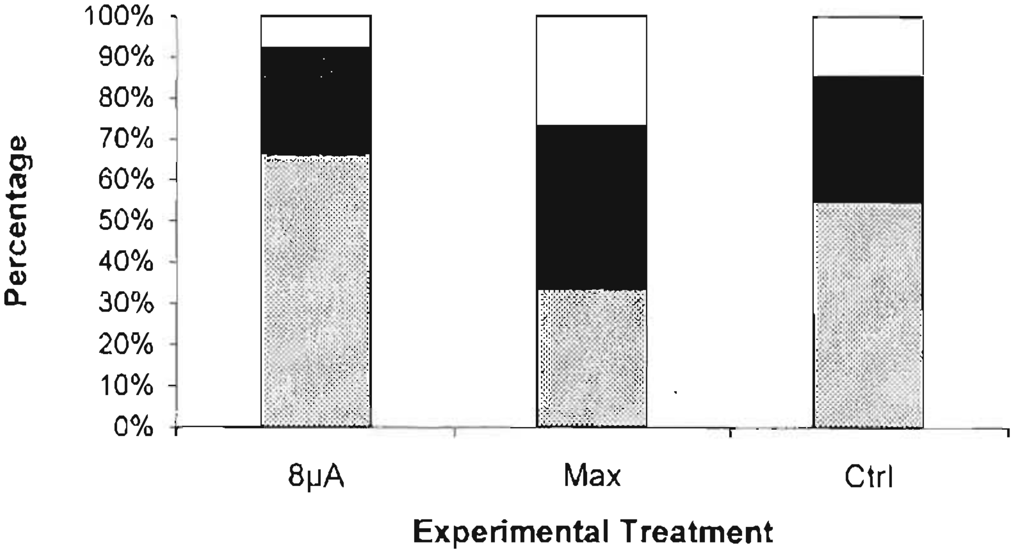

Figure 6. The spatial use of the water column directly over the electrodes expressed as a percentage of all occurrences. Categories: ☐ - At surface; ■ - Water column; ▨ - Tank bottom.

The responses recorded within the water column were not significantly different between treatments (Table 5, Fig. 6; ANOVA F=1.15, d.f.=2, p=0.325).

There was, however, a significantly greater use of the bottom of the tank by the fish in the vicinity of the experimental equipment during the 8μA treatment compared to their use during the Max treatment (Table 5, Fig. 6; ANOVA F=5.59, d.f.=2, p=0.007; Tukey post-hoc p=0.007).

3.5 Project Constraints

3.5.1 Time

The project was set up to review and undertake a pilot study into the potential effects of electric fields on elasmobranchs and to provide recommendations for further work within a three month period.

We split the project between the literature review to assess the current state of knowledge of offshore wind power generation and the electric fields produced by their undersea electric cables; current knowledge relating to electric fields in relation to elasmobranches; and a complimentary pilot experimental study.

For the experiments we encountered some difficulties which were a result of time limitation and the following factors.

3.5.2 Temperature

The water taken from the coastal Irish Sea during February and March was approximately 6-7°C, therefore the dogfish will have had a low metabolism and a low level of activity. Although we did attempt to raise the temperature of the water in one of the tanks we were limited by practical and time constraints. The issue of raised temperature may be important as we have data from other experimental studies at approximately 12 °C where we found a significant response by Scyliorhinid dogfish to a range of artificial bioelectric fields[63].

3.5.3 Species

The species that we used was again a factor of the timing of the project. The availability of elasmobranch species is different throughout the year owing to species specific life histories. In the initial proposal we aimed to test the electric fields on a ray species owing to their perceived greater requirement for electroreception in relation to their body form. Later in the year (eg. Spring) there would be an increased likelihood of obtaining sufficient numbers of a ray species. We already know, again from aquarium studies, that rays are highly sensitive to electric fields and are likely to have a species specific range of response[63,65].

3.5.4 Electric fields & Electrometer

During preliminary discussions with technical staff within the Department of Electrical and Electronic Engineering it was suggested that electric fields emanating from underwater cables could be directly measured if the appropriate recording instrument was constructed and adjusted during testing. Following further investigation and design it appears more difficult than first anticipated. The alternative to direct measurement is to use predictive mathematical tools to determine the electric fields produced by underwater dipoles and cables.

Hence, at present mathematical prediction is the most appropriate method to use to provide a measure of electric fields. Our attempts to produce and directly measure the electric fields failed.

3.6 Conclusions

Although the project was undertaken over a relatively short period of time there are a number of conclusions that come as a consequence of the research:

1. There is a dearth of objective and definitive published information relating to the question of whether electric fields produced by underwater cables have any effect on electrosensitive species (see Table 1)
2. Preliminary research has demonstrated that the benthic shark, *Scyliorhinus canicula*, avoids electric fields at 1000μV/cm which are the maximum predicted to be emitted from 3-core undersea 150kV, 600A cables
3. The avoidance response of the dogfish of 1000μV/cm electric fields was highly variable amongst individuals and had a relatively low probability of occurring in the conditions presented in these experiments
4. The same species individuals were attracted to a current of 8μA (representing an electric field of field of 0.1μV/cm at 10cm from the source), which is consistent with the predicted bioelectric field emitted by prey species.

4. FURTHER WORK

The primary aim of this research was to determine if the electromagnetic fields emitted by undersea power cables are likely to be detected and affect electrosensitive species. Although the research has demonstrated that there is an effect in terms of the behavioural response of the dogfish there remain a number of very important questions that need to be addressed to determine the potential importance of the effect. This should now become the primary aim of further work.

There are two perspectives that need to be taken into account in an unbiased and balanced manner. Firstly, in light of the current and future importance placed on renewable energy resources we need to be confident that associated human activity will not be significantly detrimental to a component of the global ecosystem not previously considered. Secondly we need to be conscious of the real need for alternative energy resources and not use effects predicted from limited, controlled laboratory investigations as conclusive evidence to heavily influence the prioritisation of renewable energy resource utilisation.

To these ends we suggest the following avenues of investigation:

4.1 Biological Projects

- Definitive longer term studies (at least 3-5 years) are required to ascertain the relevance of avoidance behaviour by elasmobranchs from an ecological perspective ie. If certain individuals are affected does this reduce/increase their likelihood of survival, gaining resources and/or reproduction and potential recruitment. These are inevitable questions that arise from these types of investigations but they should remain the central focus of studies into the 'effects of wind power derived electricity'.
- Shorter term species specific studies to determine the potential degree of response of the Irish Sea species to electric fields produced by underwater cables. This may also include other species if the study is to be geographically extended.

- Intraspecific investigations to determine the extent of individual variability in response to electric fields. In addition, these studies can look towards reasons for the variability and provide a foundation for interspecific comparisons. Intra- and Interspecific studies will require carefully planned studies potentially utilising modern individual marking/tagging techniques.
- Temperature dependent studies to investigate how electroreceptive fish respond to electric fields under different temperature regimes. Temperature also has an influence on the extent to which electric fields dissipate in water hence these studies can address two important variables in the overall project.
- Season dependent studies will be required owing to differential ecological requirements of species individuals, which are likely to be more or less sensitive to the predicted electric fields.
- Habitat use by the different species at different life stages. These studies would consider whether species are likely to be attracted to a particular geographic location at any point in the lifecycle or at specific times of the day/year. These data would be a crucial aspect within the process of site location and cable laying routes and operations, as these may have to be reconsidered or timed appropriately. In addition, there is potential that there will be differential sensitivity with ontogenetic stage particularly in shallow nursery areas where the electric cables are likely to cross or be buried.

Important note: laboratory based studies will require animal welfare licensing approval.

4.2 Electric Field Projects

Through the present project it has become apparent that the greater use of undersea cables and the proposed increase in offshore structures associated with energy transmission has taken into consideration the potential effects on electrosensitive species. Many of the topics that need to be considered (such as effects on different species, temperature effects, depth effects, substratum effects, cabling combinations etc.) require the input of marine electrical engineers. The physics and mathematics involved with electromagnetic fields in the aquatic environment are central to our understanding hence there needs to be a significant component of the analyses of any effects of these fields to be discussed and considered by appropriately qualified personnel who are sympathetic to environmental considerations. Hence, a bidisciplinary study is required to significantly promote the project bringing a marine biologist and marine electrical engineer into close collaboration to address the specific objectives.

A major potential exists for projects to continue the development of methods for predicting and directly measuring the electromagnetic fields within the experimental tanks and also *in situ*. A project of this nature can investigate the variability of field strength in relation to such factors as temperature and substratum, which would provide a close link with the biological projects.

In addition, there is a requirement to further investigate how power generated offshore is transmitted through underwater cables, for example:

- What are the maximum and minimum currents required to pass through the cables and is there a peak at a particular time of day?
- If maxima and minima occur can the timing of electricity transmission be partitioned to reduce the likely effects owing to differences in time of year and/or diurnal variation in response of electrosensitive organisms?
- What is the potential for storage facilities or staging posts to regulate the transmission of the electricity?
- Which cable configurations are the best to minimise the potential effect of the electric fields generated and also maximise efficiency of power transmission?
- What types of substratum are the best to reduce the electric field effect in relation to the practicalities of actual burial? This aspect is also important in relation to species habitat preferences and the potential conflict of preferred burial substratum.
- Are magnetic fields a potential confounding influence on the electric fields emitted by undersea cables and therefore the response of electrosensitive species?

4.3 Geographic Information System (GIS) Based Projects

If the biological work demonstrates a significant effect on the fish then there needs to be due consideration of the need to dampen this effect possibly through burial of the cable which is responsible for emitting the electric field. The electric fields emitted from undersea cables are a function of the depth of burial of the cables. Therefore burial depth and substratum type form a very important component of future work which is likely to significantly influence logistic and economic considerations of any offshore development. The types of benthic, marine substrata that exist between the offshore installation and the onshore collection point will have ramifications for any development.

The benthic habitat types, therefore, require classification for each prospective site for wind power installation. Through the application of GIS, plans for prospective installations and cabling routes can be superimposed on benthic habitat classification maps. This information can then be interrogated in relation to benthic habitat that is used by electrosensitive species. The data can be partitioned into species, habitat/substratum preference, time of year and life history stage to determine potential conflicts that may arise by proposed offshore developments and cabling routes. In addition, navigation routes, other environmental interests and prevailing wind paths can also be overlain within a GIS (subject to available information) to provide the best options for the location of windpower sites.

In summary there are three areas of work that need addressed and resourced based on the findings of this preliminary study:

- Further directed biological research, especially focussing on species use of the inshore habitats and behavioural responses to electric fields.
- Electric field research, in particular the quantification of fields within different substrata and *in situ* measurement.
- GIS mapping and interrogation, to provide a database, which can guide decisions on the location of offshore windpower sites taking into account potential conflicts with elasmobranchs.

4.4 Resource Requirements

The potential for utilising offshore wind resources is undeniable and promotion of renewable resources is crucial for our future. It is, however, imperative that the development of new technology such as offshore windpower is sympathetic to other environmental considerations.

The projects identified above and the fact that offshore wind power technology is in its infancy, embraced by just six countries worldwide, promotes the requirement for substantial support and investment into the development of renewable resource utilisation and understanding its role within the natural ecosystem. For example, the benefits of windfarms in the protection of some critical habitats from fisheries activities may outweigh their disbenefits, provided that the effects of cables on electroreception can be minimised.

4.5 The Future?

In the short to medium term there should be a concerted consideration of the environmental effects of increased wind power technology development in our coastal seas and promotion and support for initiatives that investigate offshore wind power and its role in the modern environment. This will not only increase our ability to predict environmental perturbation and improve the process leading to environmental regulations and legislation but will provide a platform to show how new technology can work with and around the natural constraints on the system.

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