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Report of the Study Group on Environmental Impacts of Wave and Tidal Energy (SGWTE)

29–31 March 2011

Edinburg, United Kingdom

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CIEM Conseil International pour l'Exploration de la Mer

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Contents

Executive summary

The Study Group on the Environmental Impacts of Wave and Tidal Energy (Chair: Michael Bell, UK) met for the first time in Edinburgh, UK, 29–31 March 2011. The meeting was attended by eight participants from Ireland, Portugal, Sweden and the UK (Scotland and England). The wave and tidal energy industry is developing rapidly and there are great aspirations for it to contribute to meeting global energy demands. The industry is a relative newcomer to the marine environment must co-exist with many other sea-users and stakeholders such as fisheries, nature conservation and shipping. SGWTE is convened as a new group to focus on the potential for wave and tidal energy developments to have consequences for the environment and other sea-users.

Given the nascent state of the industry, there are few direct observations from which to judge the nature and scale of any impacts. However, a number of recent reviews have identified the issues of greatest potential importance, and in 2010 ICES issued advice to OSPAR on the environmental interactions of wave and tidal energy devices. Much research is currently underway aiming to improve our understanding of potential impacts and to improve the information base for decision-making about future developments. SGWTE focused its attention on current research and has provided a preliminary collation of ongoing and planned research activities as well as of the state of development of the wave and tidal industry in ICES nations. The intention, as this exercise continues and is extended, is to provide improved access to new research findings, integrating these into an overall framework of information to support planning and management of wave and tidal energy activities and identifying research gaps currently hindering such planning and management. SGWTE members agreed unanimously that identifying and highlighting research gaps is the most important activity for the group. Future activities of SGWTE will include refining and updating this list of research gaps, and hopefully moving topic from the list of gaps to the lists of ongoing research activities and their outputs.

1 Opening of the meeting

The first meeting of the Study Group on Environmental Impacts of Wave and Tidal Energy (SGWTE) was held at the Scottish Government building at Victoria Quay, Edinburgh, UK, 29–31 March 2011. Delegates to the meeting were welcomed by Phil Gilmour, Head of the Marine Renewables and Offshore Wind Branch, Marine Scotland. A complete list of participants is given at Annex 1. Terms of Reference for the meeting are given in Section 3.

2 Adoption of the agenda

The Agenda given at Annex 2 was adopted by the meeting, noting the original Terms of Reference for the meeting together with additional Terms of Reference supplied by the Marine Strategy Framework Directive Steering Group (MSFDSG) and the Strategic Initiative on Area Based Science and Management (SIASM); (Section 3).

A large part of the first SGWTE meeting was spent in individual presentations in which each member of this new group had the opportunity to present a perspective on the environmental and socio-economic issues related to the development of the wave and tidal energy industry. Summaries of some of these sessions are given in Section 4. A group visit to the premises of major wave energy developer on the afternoon of Day 1 provided an opportunity to see a wave energy extraction device 'in the flesh' and to hear a developer's perspective on environmental issues (Section 5).

The meeting agreed that the remit of SGWTE was to go further than to review the potential impacts of wave and tidal energy developments. A number of such reviews have already been conducted (e.g. Gill 2005, Inger *et al.* 2009, Copping & O'Toole 2010, ICES 2010a, 2010b, Shields *et al.* 2011) and there is a high degree of agreement on the most important issues. Much of this is already summarized in ICES advice to OSPAR in 2010, appended at Annex 5 of this report. Further information is given in a recent report compiled by Bell & Side which is appended as a Working paper to this report (Annex 6). SGWTE members decided that there was a much greater need to collate information on current research that is moving forward our understanding of the potential consequences of wave and tidal energy developments, and even more importantly to identify the research gaps that hinder the capacity to plan and manage wave and tidal energy development activities. These issues are addressed as ToR a) and reported in Section 6. Current information was also collated on wave and tidal energy activities by ICES nations, addressed as ToR b) and reported in Section 7. The tables given in Sections 6 and 7 remain incomplete and represent the start of an ongoing task of extending and updating to be continued at future SGWTE meetings.

Sections 8 to 10 report briefly on discussions on how SGWTE activities relate to those of other ICES Expert Groups and to the Stategic Initiative on Area Based Science and Management (SIASM) and the Workshop on the Science for area-based management: Coastal and Marine Spatial Planning in Practice (WKCMSP).

2.1 References

Copping, A.E., and O'Toole, M.J. 2010. OES-IA Annex IV: Environmental Effects of Marine and Hydrokinetic Devices. Report from the Experts' Workshop, September 27th-28th 2010, Clontarf Castle, Dubline Ireland. US Department of Energy, Contract DE-AC05-76RL01830.

Gill, A.B. 2005. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. Journal of Applied Ecology, 42, 605-615.

ICES. 2010a. Report of the Working Group on Ecosystem Effects of Fishing Activities (WGECO). ICES CM 2010/ACOM:23.

ICES. 2010b. Report of the Working Group on Integrated Coastal Zone Management (WGICZM). ICES CM 2010/SSGHIE:05.

Inger, R., Attrill, M.J., Bearhop, S., Broderick, A.C., Grecian, W.J., Hodgson, D.J., Mills, C., Sheehan, E., Votier, S.C., Witt, M.J., and Godley, B.J. 2009. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. Journal of Applied Ecology, 46, 1145-1153.

Shields, M.A., Woolf, D.K., Grist, E.P.M., Kerr, S.A., Jackson, A.C., Harris, R.E., Bell, M.C., Beharie, R., Want, A., Osalusi, E., Gibb, S.W., and Side, J., 2011. Marine renewable energy: The ecological implications of altering the hydrodynamics of the marine environment. Ocean & Coastal Management, 54, 2-9.

3 Terms of Reference

2010/2/SSGHIE14 The **Study Group on Environmental Impacts of Wave and Tidal Energy** (SGWTE), chaired by Michael Bell, UK, will be established and will meet in Edinburgh, Scotland, UK, 29–31 March 2011 to:

a) Review and consider recent research into the state of art knowledge concerning environmental and social impacts of wave and tidal energy;

b) Review and report on ongoing activities of wave and tidal energies in ICES Member States;

c) Evaluate potential for collaboration with other EGs in relation to the ICES Science Plan and report on how such cooperation has been achieved in practical terms (e.g. joint meetings, back-to-back meetings, communication between EG chairs, having representatives from own EG attend other EG meetings).

SGWTE will report by 29 April 2011 (via SSGHIE) for the attention of SCICOM.

In addition to the original Terms of Reference (ToR), two additional sets of ToR were added relating to groups created jointly by SCICOM and ACOM (JJ/MB/vp/mo B.10).

From the Marine Strategy Framework Directive Steering Group (MSFDSG), the following ToRs were added to all Expert Groups during 2011:

- Identify elements of the EGs work that may help determine status for the 11 Descriptors set out in the Commission Decision (available at http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:232:0014:0024:EN:PDF;
- Provide views on what good environmental status (GES) might be for those descriptors, including methods that could be used to determine status.

From Strategic Initiative on Area Based Science and Management (SIASM), the following ToRs were added to all EGs for 2011:

- Take note of and comment on the Report of the Workshop on the Science for area-based management: Coastal and Marine Spatial Planning in Practice (WKCMSP) http://www.ices.dk/reports/SSGHIE/2011/WKCMSP11.pdf

- Provide information that could be used in setting pressure indicators that would complement biodiversity indicators currently being developed by the Strategic Initiative on Biodiversity Advice and Science (SIBAS). Particular consideration should be given to assessing the impacts of very large renewable energy plans with a view to identifying/predicting potentially catastrophic outcomes.
- Identify spatially resolved data, for e.g. spawning grounds, fishery activity, habitats, etc.

4 Introductory presentations

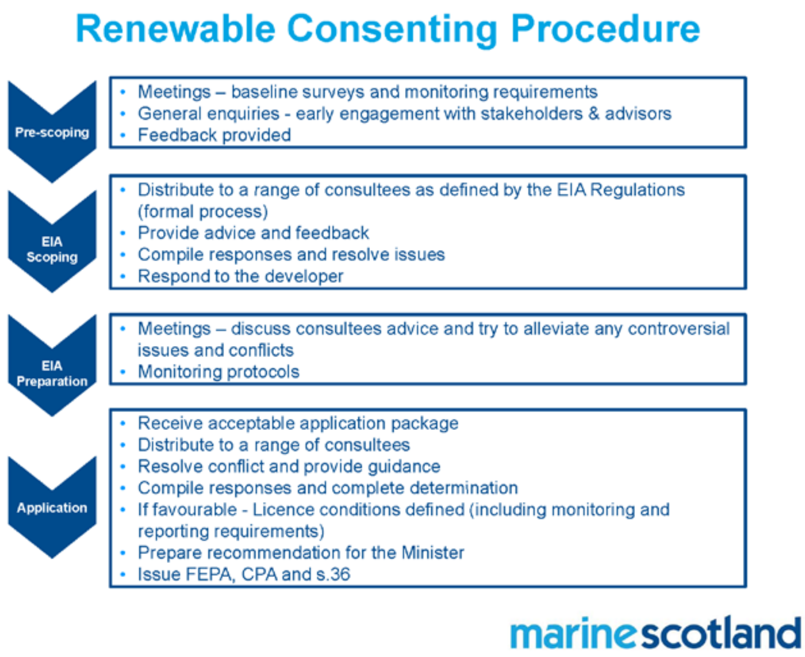
4.1 Michael Bell (UK) – Marine renewables: Orkney connections

Pentland Firth and Orkney Waters is the first area in the UK made available for commercial scale development of wave and tidal energy. The UK Crown Estate has entered into agreements for projects in this area with a capacity of 1 200 MW, equally split between wave and tidal. The Orkney area is thus a focus for research into the environmental implications of extracting hydrokinetic energy from waves and tides. Research topics include:

- Resource modelling – good information exists at large scales, but much more is needed to be know about fine scale distribution at the level of sites.
- Effects of energy extraction on physical processes – there is a good background of research approaches, but there remains a need for explicit and site-specific modelling of energy extraction.
- Implications for ecological processes of changes in physical processes – the principles by which ecological processes are likely to be modified are reasonably well understood, but there is a need for whole system modelling.
- Direct effects of energy extraction devices on habitats, biotopes and species, e.g. through noise and collisions – these are reasonably well addressed in current research programmes, but more research is needed on monitoring methods.
- New ecological space provided by developments, such as reef effects and devices acting as fish aggregation devices – there is a good theoretical background, and experience from other industries (e.g. oil and gas) is informative, but there is a need for device-specific studies.
- Interactions of the wave and tidal industry with other sea users, especially the fishing industry – much relevant spatial information exists and is used in locational guidance, but whole system modelling is needed.
- Crossing the land-sea boundary, especially in terms of infrastructure needed to bring energy ashore – this seems to be an overlooked topic at present, with no obvious connection between land- and sea-based planning systems.

4.2 Ian Davies and Ross McGregor (UK) – Marine renewables: issues and the need for development

Spatial information systems are being used by Marine Scotland to identify suitable sea areas for wave, tidal and wind energy developments in relation to conservation designations (RAMSAR, SAC, SPA, SSSI, MNR, NNR, LNR) and shipping lanes in Scottish waters as well as the distribution of the energy resource. Consents for developments in Scotland have been complicated by requirements under diverse legislation, stimulating the development by Marine Scotland of a streamlined consenting procedure:



A problem for consenting is that it is difficult to predict effects of developments on mobile species in the absence of empirical data or an evidence base. This is particularly important in relation to SACs/SPAs (HRAs). There is potential for impacts on seabed habitats, mammals, seabirds and fish, particularly migratory species. Forms of interaction with wildlife could include physical collision, reaction to construction and operational noise, displacement and disturbance, operational 'barrier effects' and interference with migration (e.g. from electromagnetic fields and noise). We need validated models of these interactions and their consequences, but lack the technology to accurately detect and record subsea interactions. Time and resources are needed to understand target populations of mammals and birds such that any impacts of renewables can be reliably detected and correctly assigned. There is some existing knowledge, e.g. from the JNCC/ESAS data base, information on the foraging range of seabirds, information on impacts from already constructed windfarms. Currently planned research includes aerial surveys of seabirds in the Pentland Firth and Orkney Waters and research into the potential for collision impacts from tidal turbines. Potential interactions with other users is another important issue for consenting. There is a need to understand the implications of displacing fishing effort. VMS systems give good information on the distribution of fishing activities by >15 m vessels, but there is relatively little information on smaller vessels. Advice is needed on potential impacts on coastal processes, including sediment transport, erosion and deposition, changes in wave climate affecting recreational users and coastal habitats.

Potential for positive effects can also be identified. It is relevant to ask, for example, what other activities may be compatible with some forms of renewables developments for multiple use of sites? In principle, there should be potential for developments to function as Marine Protected Areas to support conservation and commercial fisheries. It is also important to address the issue of securing socio-economic benefits at a local as well as national scale.

A number of issues can be seen on the horizon:

- Significance to be given to Priority Marine Features?
- Significance and management of landscape /seascape /NSA/remoteness issues?
- How can local communities be brought into the economic processes. How can they benefit?
- How does tourism fit into the mix?
- Logical basis for tradeoffs between different uses of the sea?
- When is enough enough? Limits to growth?
- What is the change in balance of issues as the scale of development increases/ Do any new issues arise?

Marine Spatial Planning is a new challenge.

4.3 George Lees (UK) – Developments in Scotland

Though still in its infancy, the tidal-stream energy sector is due to expand, rapidly, in Scotland over the next decade. At present there are just two operational grid-connected demonstrator devices in the water, both at the European Marine Energy Centre (EMEC) test facility off Eday, in Orkney www.emec.org.uk/tidal_site.asp. These are operated by OpenHydro and by TGL (Tidal Generation Ltd.). Five berths remain for further tidal devices, most of which are likely to be occupied by the end of 2011. A non grid-connected 'scale' or 'nursery' site for the testing of scale devices and deployment and retrieval methodologies is also due to become operational later in 2011, off the island of Shapinsay.

In March 2011, consent was given to Scottish Power Renewables for the construction of a 10MW tidal-stream array in the Sound of Islay. If constructed by 2013, as planned, this could be the first operational tidal array in the world.

In March 2010, the Crown Estate announced the award of lease agreements for four commercial tidal-stream arrays in the Pentland Firth and Orkney (along with six wave-power arrays; Figure 1). A fifth tidal energy scheme was added later that year. The award of a lease guarantees the developer exclusive use (for energy production) of the area of sea concerned, but consent from the industry regulator (Marine Scotland) still needs to be obtained. The five tidal schemes will, if consented, have a combined generating capacity of 1GW, and range from 100–400MW per scheme. Most developers plan a phased build-up of their arrays but hope to have the initial phases operational by 2015.

Further agreements for lease for commercial and demonstrator arrays are due to be announced imminently through the Crown Estate and Scottish Government's 'Saltire Prize' leasing round. These are likely to be focused around the Mull of Kintyre and the Islay, in south-west Scotland (Figure 2). Lease agreements for a small number of additional demonstrator schemes, elsewhere in Scotland, are due to be announced at the same time. Up to date details can be obtained from the Crown Estate website: www.thecrownestate.co.uk/wave-tidal.

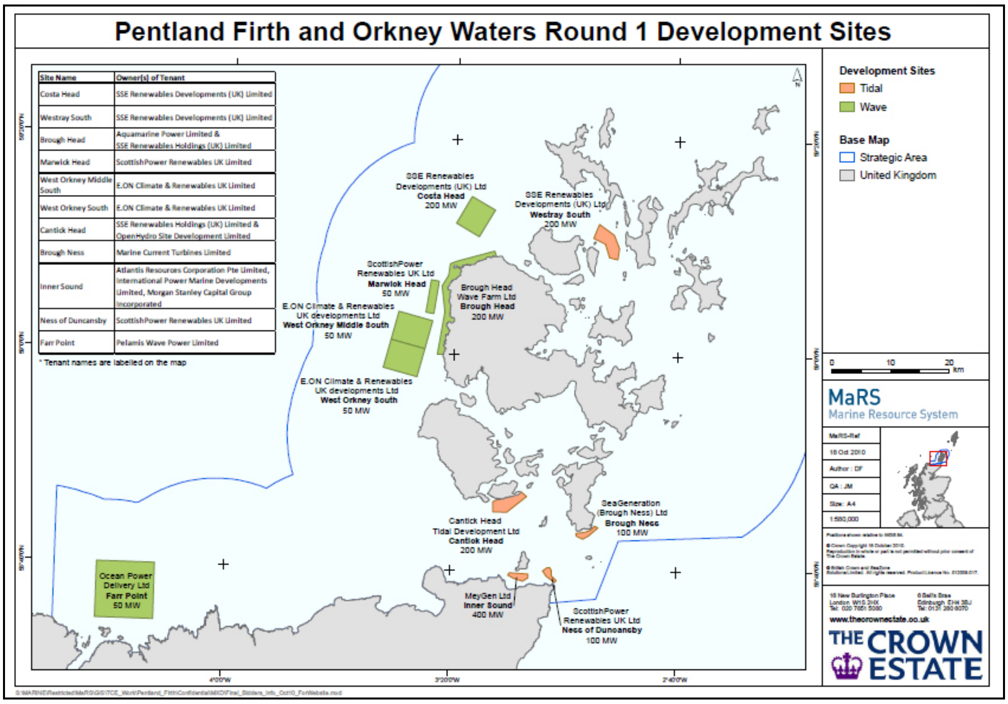


Figure 1. Pentland Firth and Orkney Waters Round 1 Development Sites.

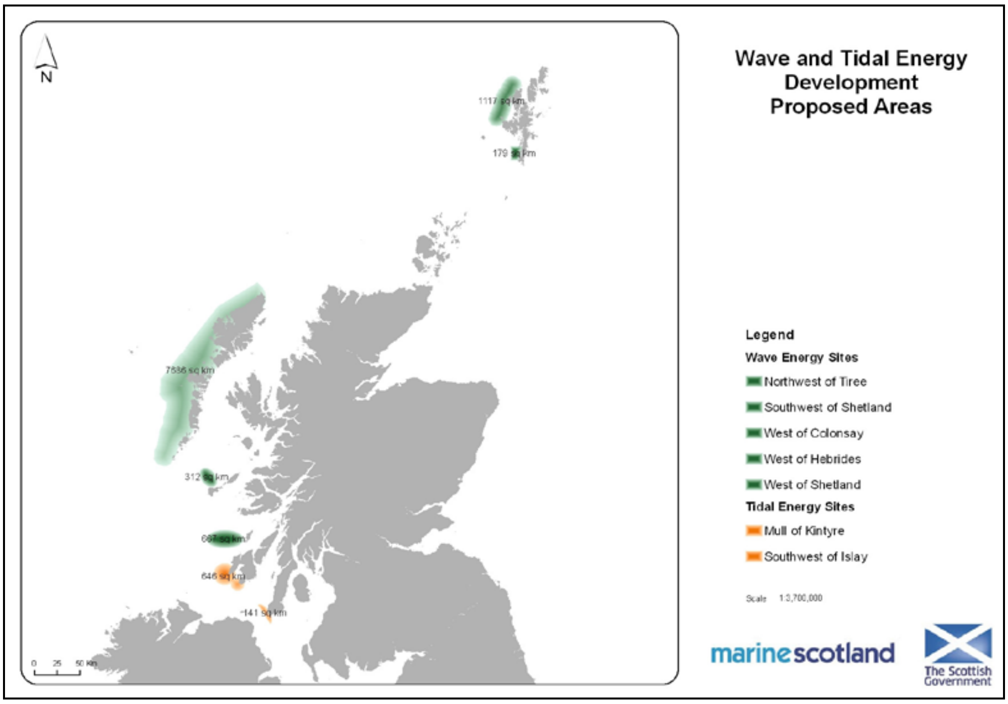


Figure 2. Scottish leasing round (Saltire prize projects) proposed areas.

4.4 Anne Marie O'Hagan (Ireland) – Issues and activities relating to environmental interactions: Ireland

This presentation provides an overview of the wave and tidal energy test centres that are in operation and planned for development in Ireland. These overviews include a description of the physical characteristics of the sites as well as the environmental surveying and monitoring work that has been carried out to date or is currently underway. At the Galway Bay test site no pre-environmental monitoring or EIA was carried out prior to device deployment. A small-scale marine environment appraisal was however carried out in 2010, the results of which are presented here. At the Atlantic Marine Energy Test Site (AMETS), a full EIA is underway and a post-EIA monitoring plan is out for tender. The site is expected to become operational in 2012. In Northern Ireland the SeaGen tidal device in Strangford Lough has been operational since 2008. The regulatory agencies responsible with the developer employed an adaptive management approach to environmental monitoring which is summarised briefly here. To conclude the issues arising, related primarily to a lack of baseline data and limited resources, are outlined with potential opportunities explored. The latter refer to the use of test centres as research platforms as well as expansion of research capacity in marine science-related disciplines.

4.5 Rory O'Hara Murray (UK) – A review of recent tidal energy modelling work

There are a number of methods to obtain first order estimates of the energy extraction potential at prospective tidal energy sites. The Kinetic flux method provides a good measure of resource intensity. It does not, however, take into account the changes to the flow that results from the presence of tidal energy devices. It is therefore a poor predictor of the true extraction potential. Recently, a number of one dimensional models have provided alternative tools. These models also show that there is an inevitable trade-off between energy extraction and the physical impact on the environment, such as changes in the tidal currents and ranges. This work examines a number of generic modelling scenarios and highlights a number of issues that need addressing. In particular, the interconnectivity between devices and their cumulative effects on a regional scale are discussed. This emphasises the need for site-specific assessment of potential environmental effects. It is therefore important for Marine Scotland-Science to develop the appropriate modelling tools to assess any such potential impacts on the physical environment to inform the licensing and marine spatial planning process.

5 A wave energy developer's perspective

SGWTE members visited Pelamis Wave Power Ltd at their premises in Leith, Edinburgh, hosted by Ros Hart and Laura Carse. The group was shown the new Pelamis P2 device under construction and were told about the company's activities in relation to potential environmental impacts. Laura Carse provided the following perspective on research needs:

We [Pelamis] are undertaking our own review to identify environmental monitoring requirements which will support our consenting operations for both ourselves and our customers. However, at a higher level we would ask that any authority considering research priorities should focus on:

Immediate need to gather data on real sea, full-scale deployments

From the perspective of the developer, there has been a great deal of funding allocated to generic projects with outputs geared towards developing protocols, guidance etc. We are in a situation now, where much robust guidance is coming from the organisations that regulate us (e.g. Marine Scotland and SNH) and believe that funding opportunities can now be focused in much more closely with the sector. Whilst generic research has played a role in establishing a platform and expertise for further work, we would encourage potential academic partners and institutes to form strong consortia with industry (technology and project developers) to undertake machine-specific monitoring. Consenting in the current dynamic regulatory environment brings a number of obstacles, with project developers and regulators alike unable to proceed confidently without real data gathered through monitoring around real sea deployments. This data would:

- Facilitate regulators to comfortably make decisions within the European and national legal frameworks;
- Scope out effects which are unlikely to result in adverse interactions with machines, and target baseline and post consent monitoring on the basis of known risks;
- Reduce consenting uncertainly and blanket approach (also expensive and time-consuming) of the 'precautionary principle'.

Consider Findings or 'State of the Art' from Comparable Marine Technologies

Wave energy converters are often considered as 'new' or 'novel' technologies, however many MECs are based on standard technologies employed in offshore oil and gas, aquaculture and port facilities. Pelamis, for example, is moored with drag embedment anchors which have a history extending as far back as 2 000 BC, based on the principle that weight as well as a certain degree of friction on the bottom which secured a vessel in position. Many concerns are raised regarding electrical cables, however a glance at any Kingfisher Cable Awareness chart shows the level of subsea telecommunication cables, pipelines and interconnectors already present on the UK seabed. Acoustic outputs are also raised as an issue, however has any assessment been undertaken regarding the 5 350 tonnes of ferry crossing the Pentland Firth and the two 9 cylinder MAK Diesel units providing a maximum of 8 680 kW several times a day? Floating Production, Storage and Offloading Units (FPSOs) are located in numerous locations around the north sea and are essentially semi-permanent vessels moored to the seabed and a number of similarities can be drawn with Pelamis machines.

Regional initiatives

Some site specific surveys are considered unlikely to provide statistical power required to detect population changes (e.g. marine mammals). Targeted regional monitoring initiatives can provide significant value in terms of both strategic planning , data to inform developer-specific EIA and also provide the regulator with the 'bigger' picture when setting baseline monitoring requirements and consent conditions.

Risk Assessment

Early indications of the regulation of the wave and tidal sector showed some signs of wholesale transferral of offshore wind regulation to the emerging marine energy sector. Whilst this has now been acknowledge by regulators to be inappropriate for most technologies, there is a need to assess the actual risks that the technology poses and apply the outcomes logically to the deployment site to determine the true risk that the machine poses. This is a basic premise of the EIA regulations but we have not seen robust evidence of auditable risk assessment to date. This may be addressed in the Impacts Report currently being undertaken by Aquatera.

6 Recent research into the state of art knowledge concerning environmental and social impacts of wave and tidal energy (ToR a)

The following table contains information compiled by SGWTE on current environmental and social research activities relating to wave and tidal energy. The tables are incomplete, but represent a starting point for future SGWTE activities. A table identifying important research gaps is also provided in this section – again, it will be important to add to this table in future, and to move items to the table of ongoing research when these research needs are addressed.

6.1 Current research activities

Project title	Framework	Research providers	Funding Source	Time-line	Geographical relevance	Generic relevance	Project description
Advancing Marine Renewable Energy Capabilities in Scotland	MREDS Work Package 5	Heriot-Watt University (ICIT), UHI (Environmental Research Institute) (UK)	Scottish Funding Council (Strategic Research Development Grant)	2008–2011	Hydrographic modelling and survey data for Pentland Firth and Orkney Waters	Spatial fishery modelling, nature of impacts	Development of research capacity relating to the development of wave and tidal energy in Scotland
Monitoring methods	SuperGen Marine 2 Work Stream 10	Heriot-Watt University (ICIT), Queens University Belfast (UK)	UK Engineering & Physics Research Council	2008–2011	Littoral and Subtidal environments of Orkney, Strangford Lough tidal turbine site	Development of generic ecological monitoring tools	Development of monitoring tools to detect ecological responses to extraction of energy from waves and tides
Hydrographic modelling	Energy Technology Partnership (ETP)	Heriot-Watt University, Strathclyde University (UK)	UK Engineering & Physics Research Council	2011–2014	Hydrographic modelling and simulation of energy extraction scenarios for Pentland Firth and Orkney Waters	Development of modelling approaches, generic information on potential spatial scales of impact	PhD studentship
Passive acoustic monitoring of diving seabirds	MREDS Work Package 5	Heriot-Watt University, RSPB, EMEC (UK)	Total Fondation and Total E&P, Aberdeen	2008–2009	Testing monitoring tools in Orkney Waters	Development of acoustic monitoring tools for diving birds	Detection and identification of diving bird activity by 'SonoBuoy' mounted hydrophones

Project title	Framework	Research providers	Funding Source	Time-line	Geographical relevance	Generic relevance	Project description
Monitoring and evaluation of Spatially Managed Areas (MESMA)	FP7	IMARES (NL), University College London (UK), Senckenberg (DE), Ughent (BE), HCMR (GR), IO-BAS (BG), IMR (NO), University College Cork (IE), CNR-IAMC (IT), Tecnalia AZTI (ES), MRAE-MCFS (MT), DTU AQUA (DK), Cefas (UK), Heriot-Watt University (UK), ILVO (BE), Deltares (NL), NIVA (NO), TNO BenO (NL)	EU	2009–2013	Pentland Firth & Orkney Waters case study on wave and tidal energy, case studies elsewhere on other topics	Development of generic tools for Marine Spatial Planning	Focuses on marine spatial planning and aims to produce integrated management tools for monitoring, evaluation and implementation of Spatially Managed Areas.
Methods monitoring wave exposure	Supergen Marine 2	Heriot-Watt University (UK)	UK Engineering & Physics Research Council	2008–2011	Trial monitoring of wave exposure on Orkney shores	Development of generic monitoring tool for wave exposure	PhD Studentship developing and demonstrating inexpensive and efficient device to measure level and dominant directions of wave exposure on rocky shores at biologically meaningful spatial scales
WEAM - Wave Energy Acoustic Monitoring	FCT (Portuguese National Science Foundation)	WavEC (PT), Univ. Alg. (PT)	FCT (National Science Found. Portugal); ~150k€	2008–2011	Pico/Azores and Peniche (Portugal)	Relatively high	Development of a hydrophone-based underwater sound monitoring methodology for wave energy devices; numerical propgation models; test measurement and evaluation process on two real-scale projects.

Project title	Framework	Research providers	Funding Source	Time-line	Geographical relevance	Generic relevance	Project description
Waveplam - Wave Energy Planning and Marketing	IEE (Intelligent Energy Europe)	EVE (co-ordinator); WavEC responsible for task on "Non-technical barriers"	EC-IEE 2007 (Intelligent Energy Program of the EC); ~1M€	2007–2010	Europe	Relatively high	(not research but discussion of extent to which environmental impacts can be show-stoppers); Del. 2.2: Non-technological Barriers to Wave Energy Implementation
Equimar - Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact	FP7 (EC)	WavEC (PT) - WP6 lead;	EC (FP7-RTD); ~4M€ total; environmental WP ~250k€	2008–2011	Europe	Very high	Development of generic protocols for main areas of activity in pre-commercial development of wave and tidal devices; WP 6 dedicated to environmental impacts assessment (desk work, collation of existing data and information and extrapolation from related areas).
SURGE - Simple Underwater Renewable Generation of Electricity	FP7 (EC)	AWE (FI); WavEC (PT) responsable for environmental monitoring tasks within WP 8 (physical monitoring IH (PT-Hydrographic Insttute)	EC (FP7-TREN); ~3M€ total; environm. WP ~500k€ (of which large part physical monitoring)	2009–2012	Peniche/ Portugal	Low - medium	Design, construction, deployment and testing/monitoring of a 300kW rated full-scale demonstrator of the WaveRoller technology; environmental tasks included: map-supported reports on physical environment, including sediment transport characteristics and morphology development (baseline and during operation). Underwater acoustic noise, measurements and appreciation; observations of benthos at and around deployment site, including baseline considerations.
FAME - The Future of the Atlantic Marine Environment	INTERREG (EC)	Coordinator: XXXX; WavEC (PT) responsible for	EC-INTERREG Atlantic Area 2007-13; WavEC approx. 60k€	2009–2011	Portuguese Western continental coastline	Low - medium	Monitor and track seabirds throughout the Area and, by combining this data with oceanographic information, produce comprehensive maps to inform the designation of Marine Protected Areas..

Project title	Framework	Research providers	Funding Source	Time-line	Geographical relevance	Generic relevance	Project description
OES-IA Annex IV - Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal, and Current Energy Systems	OES-IA (Implementing Agreement on Ocean Energy Systems of the International Energy Agency)	PNNL (USA) - WavEC (PT) & Marine Institute (Plymouth/UK) subcontracted for database	OES-IA (Implementing Agreement on Ocean Energy Systems of the International Energy Agency); 100k€	2009–2011	Global	Very high	Collation and organisation of existing data on (potential) impacts of Marine Energy Devices; including "searchable database on environmental effects on MHK (Marine Hydrokinetic) projects" --> to be specified.
Unsteady flow	MREDS Work Package 4	Heriot-Watt University, University of Glasgow, Strathclyde University	UK Engineering & Physics Research Council	2008–2009	Not site-specific	Tidal turbine rotors	Investigations of unsteady flow over tidal turbine rotors
Wave and tidal current interactions	MREDS Work Package 4	Heriot-Watt University (UK)	Total	2006–2009	Based on data from EMEC tidal test site	Generically applicable physical modelling	Investigations into wave-current interactions, boundary layers and turbulence conditions in a tidal energy resource.
Advancing Marine Renewable Energy Capabilities in Scotland	MREDS Work Package 5	Heriot-Watt University (ICIT), UHI (Environmental Research Institute) (UK)	Scottish Funding Council (Strategic Research Development Grant)	2008–2011	Hydrographic modelling and survey data for Pentland Firth and Orkney Waters	Spatial fishery modelling, nature of impacts	Development of research capacity relating to the development of wave and tidal energy in Scotland
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Methods monitoring wave exposure	Supergen Marine 2	Heriot-Watt University (UK)	UK Engineering & Physics Research Council	2008–2011	Trial monitoring of wave exposure on Orkney shores	Development of generic monitoring tool for wave exposure	PhD Studentship developing and demonstrating inexpensive and efficient device to measure level and dominant directions of wave exposure on rocky shores at biologically meaningful spatial scales
WEAM - Wave Energy Acoustic Monitoring	FCT (Portuguese National Science Foundation)	WavEC (PT), Univ. Alg. (PT)	FCT (National Science Found. Portugal); ~150k€	2008–2011	Pico/Azores and Peniche (Portugal)	Relatively high	Development of a hydrophone-based underwater sound monitoring methodology for wave energy devices; numerical propgation models; test measurement and evaluation process on two real-scale projects.
Waveplam - Wave Energy Planning and Marketing	IEE (Intelligent Energy Europe)	EVE (co-ordinator); WavEC responsible for task on "Non-technical barriers"	EC-IEE 2007 (Intelligent Energy Program of the EC); ~1M€	2007–2010	Europe	Relatively high	(not research but discussion of extent to which environmental impacts can be show-stoppers); Del. 2.2: Non-technological Barriers to Wave Energy Implementation
Equimar - Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact	FP7 (EC)	WavEC (PT) - WP6 lead;	EC (FP7-RTD); ~4M€ total; environmental WP ~250k€	2008–2011	Europe	Very high	Development of generic protocols for main areas of activity in pre-commercial development of wave and tidal devices; WP 6 dedicated to environmental impacts assessment (desk work, collation of existing data and information and extrapolation from related areas).

Project title	Framework	Research providers	Funding Source	Time–line	Geographical relevance	Generic relevance	Project description
SURGE - Simple Underwater Renewable Generation of Electricity	FP7 (EC)	AWE (FI); WavEC (PT) responsable for environmental monitoring tasks within WP 8 (physical monitoring IH (PT-Hydrographic Institute)	EC (FP7-TREN); ~3M€ total; environm. WP ~500k€ (of which large part physical monitoring)	2009–2012	Peniche/ Portugal	Low - medium	Design, construction, deployment and testing/monitoring of a 300kW rated full-scale demonstrator of the WaveRoller technology; environmental tasks included: map-supported reports on physical environment, including sediment transport characteristics and morphology development (baseline and during operation). Underwater acoustic noise, measurements and appreciation; observations of benthos at and around deployment site, including baseline considerations.
FAME - The Future of the Atlantic Marine Environment	INTERREG (EC)	Coordinator: XXXX; WavEC (PT) responsible for	EC-INTERREG Atlantic Area 2007-13; WavEC approx. 60k€	2009–2011	Portuguese Western continental coastline	Low - medium	Monitor and track seabirds throughout the Area and, by combining this data with oceanographic information, produce comprehensive maps to inform the designation of Marine Protected Areas..
OES-IA Annex IV - Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal, and Current Energy Systems	OES-IA (Implementing Agreement on Ocean Energy Systems of the International Energy Agency)	PNNL (USA) - WavEC (PT) & Marine Institute (Plymouth/UK) subcontracted for database	OES-IA (Implementing Agreement on Ocean Energy Systems of the International Energy Agency); 100k€	2009–2011	Global	Very high	Collation and organisation of existing data on (potential) impacts of Marine Energy Devices; including "searchable database on environmental effects on MHK (Marine Hydrokinetic) projects" --> to be specified.
Unsteady flow	MREDS Work Package 4	Heriot-Watt University, University of Glasgow, Strathclyde University	UK Engineering & Physics Research Council	2008–2009	Not site-specific	Tidal turbine rotors	Investigations of unsteady flow over tidal turbine rotors
Wave and tidal current interactions	MREDS Work Package 4	Heriot-Watt University (UK)	Total	2006–2009	Based on data from EMEC tidal test site	Generically applicable physical modelling	Investigations into wave-current interactions, boundary layers and turbulence conditions in a tidal energy resource.

Project title	Framework	Research providers	Funding Source	Time-line	Geographical relevance	Generic relevance	Project description
MAREE?							
Hebridean Futures?							
SOWFIA	EU IEE	University of Plymouth and partners	EU IEE	2010–2013	Wave Hub site and others in europe	Wave energy; study of impacts assessment, includes environmental and socio-economic	coastal processes, biodiversity, socio-economics, public perception; mostly collection of existing data
MERIFIC	EU INTERREG	University of Plymouth and partners	EU INTERREG	2011–2014	Wave Hub, Isles of Scilly, Finnistere	marine renewable energy for remote and island communities	not yet funded
Wave Hub benthic research methods development		University of Plymouth	South west regional development agency	2009–2011	Wave Hub site	Generally applicable to assessing impacts on benthos	Baseline habitat mapping in advance of deployment of WECs at Wave Hub site (not yet funded)
Wave Hub vertebrates		University of Exeter	South west regional development agency	2009–2011	Wave Hub site plus Cornish coast	Generally applicable to assessing impacts on cetaceans and birds	Baseline passive acoustic studies with CPODS in advance of deployment of WECs at Wave Hub site (not yet funded)
Wave Hub hydro-dynamics		University of Plymouth	NERC	2011–2014	North cornish coast/Wave Hub site	Generally applicable to understanding impact on tidal mixing, frontal behaviour, etc	Baseline water column characterisation - upstream - downstream CTD, microstructure, ADCP, ecology
Wave Hub modelling		Plymouth Marine Laboratory	NERC	2011–2012	Wave Hub site	Generally applicable to developing array scale model	Base line ecological water column characterisation for input to generic ecosystem models

Project title	Framework	Research providers	Funding Source	Time-line	Geographical relevance	Generic relevance	Project description
Fish movements and site fidelity at Wave Hub site		Marine Biological Association	NERC	2009–2011	Wave Hub site	Generally applicable to understaning fish movements in no take zone	Landers to be deployed plus tagging of commercially significant spp
ReDAPT		Plymouth Marine Laboratory	ETI	2010–2014	EMEC	Generally applicable to both wave and tidal	Experimental studies into biofouling - devices and infrastructure to independently test whole range of coatings available
Energy and environment theme - offshore wind	UKERC	Plymouth Marine Laboratory	NERC	2009–2012	offshore coastal	development of socio-economic methods	Focus on methods development for ecosystem services valuation for offshore wind - methods transferable to wave and tidal
Marine Energy development Programme	Low Carbon research Institute	Bangor University	WEFO/ERDF	2010–2013	N coast Wales	generally applicable to similar coastal environs	Sediment dynamics , larval dispersal
Marine Energy development Programme	Low Carbon research Institute	Swansea University	WEFO/ERDF	2010–2013	Ramsey Sound, Pembs	Comparing with other population behaviours	Acoustic monitoring / effects of noise
Marine Energy development Programme	Low Carbon research Institute	Cardiff University	WEFO/ERDF	2010–2013	Bristol Channel initially	Increasing model to Welsh Coast	Hydro environmental modelling
Marine Energy development Programme	Low Carbon research Institute	Swansea Metropolitan	WEFO/ERDF	2010–2013	Bristol Channel and West Wales	Area specific	Coastal processes
Marine Energy development Programme	Low Carbon research Institute	Swansea University and Pembrokeshire college	WEFO/ERDF	2010–2013	Ramsey Sound, Pembs	Area specific but applicable to other populations	Porpoise numbers and distribution seal haul out etc
No specific title	Institute of Sound and vibration	Southampton University	DSTL / MoD	on going	all regions	generally applicable to assessing device noise	developing standards for device noise

Project title	Framework	Research providers	Funding Source	Time-line	Geographical relevance	Generic relevance	Project description
Guernsey Renewable Energy assessment	Guernsey govt	University of Plymouth		2010–2011	Channel Islands	Methods development generally applicable	testing of method at new site
RESPONSE		SMRU / SAMS / Loughbro'		2011–2014	All regions	Generally applicable to	collision risks cetaceans / birds
FLOWBEC		NOCL and others		2011–2014	All regions	Site characterisation	multi-instrumentation
EBAO		Univ of Edin *et al*.		2011–2014	all regions	Array design optimisation	

6.2 Relevance of current research activities to development life-cycle stages and impact types

If appropriate, relevance is scored as high (H), medium (M), low (L), or relevant (X) in relation to development life-cycle and type of impact. Scores are currently incomplete.

	Project Life-cycle Stage					Nature of impact/study							
Project title	Planning and pre-development survey	Installation	Operation	Maintenance	Decommissioning	Physical processes	Ecological processes	Direct seabed impacts	Direct wildlife impacts	New ecological space	Interactions with other sea users	Baselines	Impacts
Advancing Marine Renewable Energy Capabilities in Scotland	M	M	H	L	L	H	H	M	L	L	H	L	H
Monitoring methods			H			M	H					H	L
Hydrographic modelling	H		H			H	M	L				H	H
Passive acoustic monitoring of diving seabirds	H	M	M	M	M		M		H	L		H	
Monitoring and evaluation of Spatially Managed Areas (MESMA)	H										H	H	
Methods monitoring wave exposure			H			H	H					H	M
WEAM - Wave Energy Acoustic Monitoring													
Waveplam - Wave Energy Planning and Marketing													

Equimar - Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact
SURGE - Simple Underwater Renewable Generation of Electricity
FAME - The Future of the Atlantic Marine Environment
OES-IA Annex IV - Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal, and Current Energy Systems
Unsteady flow
Wave and tidal current interactions
Advancing Marine Renewable Energy Capabilities in Scotland
Monitoring methods
Hydrographic modelling
Passive acoustic monitoring of diving seabirds
Monitoring and evaluation of Spatially Managed Areas (MESMA)
Methods monitoring wave exposure
WEAM - Wave Energy Acoustic Monitoring
Waveplam - Wave Energy Planning and Marketing
Equimar - Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact
SURGE - Simple Underwater Renewable Generation of Electricity

FAME - The Future of the Atlantic Marine Environment													
OES-IA Annex IV - Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal, and Current Energy Systems													
Unsteady flow													
Wave and tidal current interactions													
MAREE?													
Hebridean Futures?													
SOWFIA	X	X				X	X	X	X			X	
MERIFIC	X	X	X			X	X	X	X	X	X	X	
Wave Hub benthic research methods development	X	X	X				X	X		X	X	X	
Wave Hub vertebrates	X	X	X				X		X				
Wave Hub hydro-dynamics	X	X	X										
Wave Hub modelling	X		X			X	X	X				X	
Fish movements and site fidelity at Wave Hub site	X	X	X	X	X				X	X	X	X	X
ReDAPT			X	X									
Energy and environment theme - offshore wind	X					X					X		
Marine Energy development Programme	X					X	X					X	
Marine Energy development Programme	X	X	X	X	X			X				X	
Marine Energy development Programme	X					X	X					X	
Marine Energy development Programme	X					X						X	
Marine Energy development Programme	X	X	X	X	X		X	X				X	
No specific title													

Guernsey Renewable Energy assessment
RESPONSE
FLOWBEC
EBAO

6.3 Research gaps

Research gaps are preliminarily scored as of high (H), medium (M) or low (L) relevance to different stages of the development life-cycle and types of impact.

	Project Life-cycle Stage					Nature of impact/study							
Research gap	Planning and pre-development survey	Installation	Operation	Maintenance	Decommissioning	Physical processes	Ecological processes	Direct seabed impacts	Direct wildlife impacts	New ecological space	Interactions with other sea users	Baselines	Impacts
Interactions of tidal energy extraction with physical processes: consideration of upscaled extraction of energy from tidal currents rather than barrages	H		H			H	M					M	H
Site/region-specific hydrographic models	H		H			H	M					H	M
Local wake structures formed from interaction of water flow with tidal turbine blades and device structures, including device-specific studies			H			H	M	H	L	L			H
Boundary-layer processes			H				H			L			
Role of wave-current interactions in modulating impacts of tidal energy extraction			H			H	M						
Distribution of fishing effort at a small spatial scales relevant to lease and development areas	H										H	H	M
Movement patterns of commercial fish and crustacean species in relation to devices and development areas			H						M	H	H		H
Large-scale sediment transport models, with consideration of implications for biotopes			H			H	H					L	H
Models for incidence/abundance of species/biotopes in terms of spatial information on physical parameters - allows future scenarios of energy extraction to be considered alongside concurrent environmental changes (climate)	L		H			H	H					L	H
Cheap and efficient tools for environmental/ecological baseline measurement and monitoring	H					H	H					H	L
Models of the consequences of displaced fishing effort (and other human activities) for impacts outside development areas	H		H				H		H		H		H

Models for fisheries management implications of fisheries exclusion from development areas	M		H				M			M	H		H
Whole system models, integrating physical and ecological processes	H	H	H	H	H	H	H					H	H
Development of predictive modelling capacity for ecological consequences of future energy extraction and climate change scenarios	H	H	H	H	H	H	H					H	H
Measuring ecological responses against a background of climate change		H	H	H	H		H		M			H	H
Measurement and monitoring protocols	H	H	H	H	H		H		M			H	H
Modelling of devices and arrays - interactions with the resource	H					H						H	M
Regional scale modelling of physical effectsx	H					H					M		H
Increased data exchange and accessibility	H					H		H	H		H	H	H
Potential for wave/tidal developments to enhance ecosystem/biodiversity	H	M	M				H		M	M	M		M
Better coordination of site assessment/characterisation data	H					M						H	
Can phypsical aspects of site characterisation act as proxies for biological features?	H					M	M	M	M			M	M
Influence of abiotic features on bird feeding location and behaviour	H		M			M	M		M			M	M
Influence of trophic features on bird feeding - and can we predict?	H						M		H				H
Approaches to connectivity (birds, mammals) without large scale tagging projects	H								H		H	H	H
Methods to detect interactions between mammals/ birds / fish and devices.	H		H						H			H	H
Predator-prey interactions in high tidal flow areas - mammal and bird behaviour	H					M	M		H			M	H
Analysis methods to integrate site-level impact assessments to population level consequences for mammals and birds	H						M	M	H			H	H
Physical consequences of large scale developments at regional (international) scale.	H					H						H	H
Technologies to observe detailed aspects of bird and mammal behaviour/collision/avoidance etc around devices	H	H	H	M					H				H
Improved models of critical parameters of behaviour required for collision models	H					M			H	M			H
Can we measure displacement/disturbance of birds/mammals? What are consequences for individuals, and populations (and in ecosystem terms)	H						M		H	M			H
Acoustic outputs, modelling of propogation, assessment of consequences.	H	M	M			H			H				H
Significance and management of landscape /seascape /NSA/ remoteness issues?	H	M	M	M							H	H	H
How can local communities be brought into the economic processes. How can they benefit?	H	M	M								H	H	
Logical basis for tradeoffs between different uses of the sea?	H		M								H	M	H
Collection of baseline geophysical data on substrates, currents, sedimentation (risk assessment), bathymetry, seismic data, waves	H	M				H	M	H				H	M
Collection of data on shipping lanes	H										H		

Collection of objective data on areas of more/less importance for fishing	H		H	
Description of migratory patterns for key fish species, including elasmobranchs, commercially important species, schooling species, sensitive and endangered species	H			H
Data on migratory routes and feeding areas for marine mammals, reptiles and birds	H			H
Data on offshore feeding areas for truly marine birds (petrels, shearwaters, etc.)	H			H
Improved data on marine biota and its spatio-temporal variation at a habitat level	H			H
Better information on grid availability and capacity	H			
Development of new monitoring techniques, especially remote controlled	H	M		H

7 Wave and tidal energy activities by ICES nations (ToR b)

SGWTE started compiling information on wave and tidal energy development activities by ICES nations. The following tables are incomplete, but represent a starting point for future SGWTE activities. SGWTE also started compiling information on national roadmaps for wave and tidal energy, expressing aspirations and timescales for the capacity of future developments. Currently the level of information compiled is very incomplete and will be held over for a full presentation in a future SGWTE report.

7.1 Wave energy

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
Belgium	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Canada									
Denmark	DanWEC	Wave Plane	2009	Floating overtopping	?	?	?	Prototype	1km^2
	Horns Rev ?	WaveStar (15kW)	2008? and Planned 2011	Fixed-mounted multi-point absorber	Pile-mounted bottom-fixed; 15m (?)	?	?	Full-scale prototype	1km^2
	Not sure	Dexawave	Planned 2011	Oscillator	?	?	?	Prototype	1km^2
	Nissum Bredning	WaveDragon (20kW)	2003	Floating overtopping	purpose-designed point mooring (slack); 15m	extensive bird data (???)	???	1:4.5 Pilot plant	???
		Dexawave	2009	Oscillator	?	?	?	?	?
		WaveStar (15kW)	2006 and 2011	Vertical Oscillation	Pile-mounted bottom-fixed; 8m	?	?	?	?
France	SEMREV / La Croisic	Searev (500kW)	Planned 2011	Combined heave/pitch point absorber	Catenary mooring (25m?)	wave and current measurements, benthic sediment studies	monitoring of sites of natural heritage, marine invertebrate monitoring	Full-scale prototype	1km^2
Germany	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
Ireland	Galway Bay	Ocean Energy Buoy	2005/2011	Floating OWC (B2D2)	Catenary mooring; 20m	Hydrophones, TPODS, CPODS	May be some mammal work on-going	1:4	.37km^2
		Wavebob	2005	Vertically oscillating point absorber	Catenary mooring; 20m	None	None	1:4	.37km^2
	AMETS	None yet	2012	neutral	Undecided	Bird	Bird	Full scale	21km^2
						Marine mammals	Marine mammals		
						Benthic surveys	Benthic surveys		
						Bathymetry			
						Water quality			
						Noise			
						EMF			
						landscape, seascape & visual assessment			
						Navigation risk			
						Wave and current data			
						Sediment transport and energy assessment			
Netherlands	Rotterdam (?)	WaveRotor 10kW (?)	2010	Pile-mounted Darrieus-Wells Turbine	bottom-fixed (piled); 5m	None reported	None reported	1:5 Demo plant (??)	~100m2
Norway	Runde Island	Fred Olsen Buldra	2004	Vertical oscillation	slack mooring	?	?	?	?

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
		Seabased	2009	Vertical oscillation	taut mooring	?	?	Demo	?
		Wavetreader	Planned 2011	Vertical oscillation	?	?	?	?	?
Portugal	Aguçadoura	Pelamis	2002/2007	Oscillator	catenary	?	?	Full scale	?
	Portuguese Pilot Zone	Pelamis	2007	Oscillator	catenary	Wave and current data, Acoustic monitoring, invertebrate surveys, benthic surveys, Sea bird and marine mammals	Wave and current data, Acoustic monitoring, invertebrate surveys, benthic surveys, Sea bird and marine mammals	Full scale	320km^2
		AWS	2004	OWC					320km^2
	Pico, Azores	Wells Turbine	1999	Shoreline OWC	Bottom-mounted shoreline plant; 7m	Sporadic airborne noise and limited underwater noise monitoring campaigns	none permanently.	1:1 Test plant	150m^2
	Peniche	WaveRoller (300kW)	Planned 2011	OWSC	gravity foundation near-shore; 12m	initial (baseline) underwater noise and benthos data	limited scheduled benthos and underwater noise monitoring campaigns; sedimentary evolution near- and inshore	1:1 Demo plant	1000m^2

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
Spain	Mutriku, Basque Country	Voith Hydro OWC 296kW	2011	Multi-turbine breakwater OWC	bottom-mounted shoreline plant; 10m	none reported.	none reported.	1:1 Demo plant	???
	Santoña, Cantabria	OPT Power Buoy 40kW (?)	Planned 2011	Point absorber	slack-moored; 40m (?)	none reported.	none reported.	1:1 Demo plant	????
	BIMEP	Various	Planned 2011	?	?	Full EIA		Full scale	5.2km^2
Sweden	Lysekil	Seabased	2006 & 2013	Vertical oscillation	?	surveys of marine invertebrates, artificial reef effects, studies on fouling and colonisation of WECs, pilot studies of seabird and marine mammals			
United Kingdom									
England	WaveHub, Cornwall	Aegyr Dinamo	2010	Vertical Oscillation	?	?	?	?	8km^2
		PB150	Planned	Vertical Oscillation	?	?	?	?	?
Scotland	EMEC-Orkney - Billia Croo	Pelamis	2010	Oscillator	Conventional anchors	Yes	Wave and current data Mammals	Full	5km^2
							Birds		
							Waves		
							Acoustics		
		Oyster	2010	Oscillator	Base plate and pin piles	Yes	As above	Full	
		Aegyr Dynamo	Proposed	Vertical Oscillation	?	Yes	As above	Full	

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
	EMEC-nursery in Scapa Flow	Various	2011	Various	Various	Yes	Mammals	Scale	~2km^2
							Birds		
							Waves		
Wales	Pembrokeshire	WaveDragon	Planned 2011	Floating overtopping	Purpose-designed point mooring (slack); 15m	???	???	???	???
N. Ireland	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
USA	Oahu, Hawaii	OPT PowerBuoy	Dec. 2009	?	?	Seabed	Seabed	Full	?
						Fish & benthos	Fish & benthos		
						Mammals	Mammals		
						Vegetation	Vegetation		
						Water quality	Water quality		
						FONSI			
	Reedsport, Oregon	10 PB150 PowerBuoys	Planned	?	?	EIA	EIA	Commercial	10MW farm = 0.125km^2
	Coos Bay, Oregon	200 PB500 PowerBuoys	Planned	?	?	EIA	EIA	Commercial	
Affiliate countries									
Australia	Portland, Victoria	OPT and Powercor Aust	2002						
	Freemantle, Western Australia	Carnegie Wave Power	2005						
	Port Kembla, NSW	Oceanlinx	2006						
Chile									
Peru									

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
South Africa									

7.2 Wave energy

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
Belgium	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Canada	Bay of Fundy-Minas Passage	Open Hydro (1MW)	2011-12	AK-1000 Mark II, horizontal axis; open centre	bottom-mounted, fully submerged; 25m (?)	(according to Test Centre requirements)	(according to Test Centre requirements)	1:1 Demo plant	???
	Nova Scotia		1984	Barrage		??	??	Commercial	???
Denmark									
France	La Rance		1966	Barrage				Commercial	??
Germany									
Ireland	none	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Netherlands	Zaamdeik (?)	Tocardo 80 kW (?)	2009	Horizontal axis	bottom-fixed (piled); 5m	None reported	None reported	1:1 Demo plant	~10m2
Norway									
Portugal	none	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Spain									
Sweden									
United Kingdom									
England									
Channel Islands	Alderney	Open Hydro							
Scotland	EMEC Orkney: Falls of Warness	Openhydro	2009	Horizontal axis, no exposed blades	Double pile	Yes	Mammals	Full	Approx 2 km2
							Birds		
							Fish		
							Currents/tidal flow		
							Acoustics		

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
		Atlantis AK-1000	2010	Horizontal axis, exposed blades	Gravity base with pin piles	Yes	As above	Full	Approx 2 km2
		Hammerfest Strom HS1000	2010	Horizontal axis, exposed blades	Gravity base with pin piles	Yes	As above	Full	Approx 2 km2
	EMEC Tidal scale site, Shapinsay Sound	Various	Later in 2011	Various	Gravity and/or anchors	Yes	Mammals	Scale	Approx 2 km2
							Birds		
							Currents		
Wales	Ramsay Sound	DeltaStream							
		WaveGen	Proposed						
N.Ireland	Strangford Lough	MCT SeaGen	Apr-08	Tidal generator	quadrapod piled base	Effort limited visual surveys of marine mammals	MMOs 24/7 manual, observed from shore	?	?
						Passive acoustic monitoring of marine mammals	No benthic surveys now (2010)		
						Aerial survey, GPS and GSM tracking of seals	Seal carcass survey		

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
						Broadscale mapping and dive survey for benthic ecology			
						Active sonar for marine mammals			
						Sub-sea noise measurements and model construction			
						Impacts on tidal energy - transects and models			
USA	Snohomish	OpenHydro	Later in 2011	Tidal turbines	?	?	?	Two 1 MW 10-meter	?
	Maine	ORPC TidGen	Later in 2011	5 tidal turbines	?	?	?	Commercial scale (3 MW)	?
Affiliate countries									
Australia	San Remo, Victoria	Atlantis Resource Corp.	2008	Nereus turbine	?	water quality inclusive of salinity, pH, dissolved solids, turbidity, impacts on local flora and fauna as well as noise and vibration monitoring	water quality inclusive of salinity, pH, dissolved solids, turbidity, impacts on local flora and fauna as well as noise and vibration monitoring	Demo? 0.15 MW	?
Chile									

ICES Nation	Location	Device deployed	When deployed	Device type	Mooring type	Environmental data collected	Monitoring activities	Test scale of device	Deployment area
Peru									
South Africa									

8 Interactions of SGWTE with other ICES Expert Groups (ToR c)

The SGWTE is a new group that met for the first time this year. It was established on the recommendation of WGICZM, the Working Group on Integrated Coastal Zone Management (now the Working Group for Marine Planning and Coastal Zone Management, WGMPCZM) in its 2010 report. Links of SGWTE with WGMPCZM are maintained through the joint membership of Ian Davies (UK).

It was noted that the Working Group on Marine Mammal Ecology (WGMME) discussed the interactions of marine mammals with renewable energy devices in March 2011. Ian Davies contributed to WGMME by correspondence, on the application of Appropriate Assessment under the Habitats Directive to tidal turbine developments. The final report was not available at the time of the SGWTE meeting.

The ICES Annual Science Conference in Gdańsk in 2011 will include Theme Session S: Extracting energy from waves and tides – what are the consequences for ecosystems, physical processes and other sea users? It is anticipated that this session will stimulate interaction with representatives of other ICES Expert Groups.

9 Marine Strategy Framework Directive Steering Group (MSFDSG)

9.1 Elements of SGWTE work that may help determine status for descriptors of Good Environmental Status

At present, SGWTE cannot identify elements of its work that would specifically help determine status for the eleven descriptors of Good Environmental Status (GES) defined under the Marine Strategy Framework Directive. However, it is worth noting that wave and tidal energy activities may exert environmental pressures that influence the achievement of GES, both negatively (e.g. habitat condition and distribution, introduction of underwater noise) and positively (e.g. moderation of fishing pressure by displacement, biodiversity enhancement from introduction of device structures). Also see brief comments below in relation to pressure indicators to complement biodiversity indicators currently being developed by the Strategic Initiative on Biodiversity Advice and Science (SIBAS). Environmental monitoring and adaptive management of wave and tidal energy developments are relevant to determining and controlling influences on GES.

9.2 Views of SGWTE on what constitutes Good Environmental Status

The nature of descriptors for Good Environmental Status is considered to be outside the scope of work for SGWTE so the group expressed no view on how GES should be defined.

10 Strategic Initiative on Area Based Science and Management (SIASM)

10.1 Report of the Workshop on the Science for area-based management: Coastal and Marine Spatial Planning in Practice (WKCMSP)

A workshop recently convened in Lisbon (1–4 November, 2010) aimed to establish the current scientific knowledge within ICES on Coastal and Marine Spatial Planning (CMSP), and to identify gaps and limitations in science to support CMSP. The group of some 38 participants identified both environmental and socio-economic science needs for CMSP, as well as the status of decision tools to support CMSP. The Lisbon workshop also agreed some key activities going forward, including commissioning two publications and making additional recommendations for a workshop to discuss the development of a multi-disciplinary case study for MSP in the ICES area, and a theme session for the ASC 2012 focussing on the integration of different economic sectors in MSP.

Although deployment of large scale wave and tidal arrays is a few years in the future in ICES member nations, the SGWTE agreed that representatives of the wave and tidal energy sector need to be linked into all these SIASM activities to ensure that their perspective is included. To a large extent the science needs required to progress planning and consenting of developing wave and tidal energy are similar to those required for CMSP – and thus the SGWTE strongly endorse any measures which promote easy access to data for all parties and the further development of decision tools to promote sustainable development of the coastal zone. In addition, the SGWTE essentially agree with the conclusions of the Lisbon workshop supporting the continuation of ICES initiatives for SIASM, not least because of the increasing intensity and frequency of issues arising from trans-boundary and cumulative impacts of development in ICES member nations' coastal zone.

10.2 Pressure indicators to complement biodiversity indicators currently being developed by the Strategic Initiative on Biodiversity Advice and Science (SIBAS)

SIBAS biodiversity indicators are not currently available, but it is possible to identify the main pressure indicators arising from wave and tidal energy developments. This might include the nature of development, how much development is occurring and where, and the amount of energy generated.

Catastrophic outcomes of wave and tidal energy developments might include major changes in tidal amplitudes at coastal locations – it will be important to identify trade-offs between the magnitude of change and the levels of energy extracted. Changes in the abundance of priority species could occur if energy extraction causes systemic far-field effects on mixing structure and circulation patterns, affecting ecological connectivity and trophic linkages. Direct effects on protected species might also occur through collision, noise and disturbance. In practice, Strategic Environmental Assessments (SEAs), Environmental Impact Assessments (EIAs) and Appropriate Assessments (AAs) should work towards preventing catastrophic outcomes. There are, however, weaknesses in these processes in the degree to which trans-boundary effects are addressed. Cumulative effects may occur at an international scale because many species are wide-ranging. Cumulative effects combining across wave, tidal and wind developments are also not properly addressed, highlighting the need for an integrated consideration of marine renewable energy as a whole. In general, interactive and cumulative multi-sectoral pressures are potentially problematic, but there is scope for trade-offs, enhancements and synergies to be identified.

10.3 Spatially resolved data

SGWTE did not have time during the meeting to discuss the availability of spatially resolved data in relation to wave and tidal energy activities. However, it was noted that data exists on the spatial extent of development and leasing areas and could be collated alongside other types of spatial data if required. There are also data (or model outcomes) on the distribution of wave and tidal energy resources; such data tends to exist for large spatial scales, there being a lack of high quality information on the fine-scale distribution of resources at a site level.

Annex 1: List of participants

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Annex 2: Agenda

Agenda for SGWTE 2011, Edinburgh, UK

Tuesday, 29 March

10:00-10:30	Welcome
10:20-10:40	Introduction and Terms of Reference
10:40-11:00	Relationship with WGMPCZM and other ICES Working Groups
11:00-12:15	Individual presentations on national wave and tidal energy developments and related environmental research
12:15-13:00	Overview of Scottish Natural Heritage involvement in marine renewables research
14:00-14:40	Continue individual presentations
14:40-17:00	Study Group visit to Pelamis Wave Power to hear about their project development activities and view the construction of their P2 device
17:00-18:00	Continue individual presentations

Wednesday, 30 March

09:00-09:30 Review of previous day's presentations

09:30-10:00 Agree common understanding of group aims and Terms of Reference

10:00-13:00 ToR (a) – recent research on social and environmental impacts of wave and tidal energy:

(i) Research needs for Marine Spatial Planning and Environmental Impact Assessment?

(ii) Research providers and funders?

(iii) Test facilities – what are the facilities and how are they being used for research into environmental interactions?

(iv) Research by topic area – what does it tell us, and what do we still need to know?

14:00-15:45 ToR (b) – ongoing activities on wave and tidal energy in ICES nations:

(i) What is currently deployed, commercially and at test facilities – types of device, locations and ratings?

(ii) What is planned to be deployed in the near future?

(iii) What are the plans for future deployment – aspirations, roadmaps and Marine Spatial Plans?

16:00-18:00 ToR (c) – scope for collaboration with other ICES groups

ToRs from Marine Strategy Framework Directive Steering Group (MSFDSG):

- Identify elements of SGWTE's work that may help determine 'Good Environmental Status'(GES) according to 11 descriptors
- Provide views on what GES might be for those descriptors and on methods that could be used to determine status

ToRs from the Strategic Initiative on Area Based Science and Management (SIASM):

- Take note of and comment on the report of the Workshop on the Science for area-based management: Coastal and Marine Spatial Planning in Practice
- Provide information that could be used in setting pressure indicators that would complement biodiversity indicators currently being developed by the Strategic Initiative on Biodiversity Advice and Science
- Identify spatially resolved data, for e.g. spawning grounds, fishery activity, habitats, etc.

Thursday, 31 March

09:00-09:30	Review of previous day's activities
09:30-10:00	Agree templates / headings for reporting on ToRs and allocate writing tasks
10:00-12:45	Individual report writing
12:45-13:00	Review writing progress
14:00-15:15	Continue individual report writing
15:15-15:30	Review writing progress and discuss final report production
15:45-16:00	Discuss contribution of SGWTE members to Theme Session for ICES ASC 2011: *"Extracting energy from waves and tides – what are the consequences for ecosystems, physical processes and other sea users?"*
16:00-17:00	Agree recommendations, provisional Terms of Reference and date for next SGWTE meeting
17:00	Meeting close

Annex 3: SGWTE terms of reference for the next meeting

The **Study Group on Environmental Impacts of Wave and Tidal Energy** (SGWTE), chaired by Michael Bell, UK, will meet in Orkney, Scotland, UK, DATE June 2012 to:

a) Update, augment (include environmental monitoring at commercial lease sites) and extend national coverage of directories for existing wave and tidal energy activities and research activities relating to environmental and socio-economic interactions, and report on progress with commercial leases and consenting processes;

b) Collate bibliography of outputs from current and recent research activities relating to wave and tidal energy;

c) Review crucial information gaps hindering the capacity to plan and manage wave and tidal energy activities, identifying progress in addressing research requirements noted by SGWTE2011 and identifying further requirements;

d) Report on the current state of development of decision-making tools and the extent to which they are supported by systemic understanding, understanding system components and the monitoring and measurement tools used to generate such understanding;

e) Compile spatial data on areas used for wave and tidal energy;

f) Report on experience and lessons learned from other industries relating to social acceptability issues and stakeholder engagement in wave and tidal energy planning and consenting processes;

g) Review Theme Session S from ASC 2011;

h) Report on interactions with SIASM and other Expert Groups.

SGWTE will report by 1 August (via SSGHIE) for the attention of SCICOM.

Supporting Information

Priority	The activities of this Group are leading ICES into issues related to the ecosystem impacts of ocean renewable energies especially with regard to the application of Marine Spatial Planning (MSP) and ICZM. Consequently, these activities are considered to have a very high priority.
Scientific justification	Term of Reference a) The pace of development by the wave and tidal energy industry is rapidly accelerating in a number of ICES nations. In order to appreciate the scale of potential impacts there is an urgent need to keep track of these developments and to integrate the body of research that is growing alongside them. Term of Reference b) It is currently difficult to keep pace with outputs from the diverse range of research relating to wave and tidal energy. A searchable bibliography of current outputs wil be a valuable resource for scientists and regulators. Term of Reference c) Current research activities are doing much to address imporant issues relating to the environmental and socio-economic consequences of wave and tidal energy developments, but in order to best direct future research resources and avoid duplication and over-emphasis on certain topics is is crucial to keep track of issues that remain unaddressed and to identify those issues that relate to the most immediate needs. Term of Reference d)

	Applied research is used to support decision-making. ToR d) is an opportunity to define best practice in the application of science in developing decision-making tools to support planning of wave and tidal energy activities. Term of Reference e) Data on the spatial extent of wave and tidal energy development areas is a crucial substrate for Marine Spatial Planning and analyses of the portential for wave and tidal energy to interact with other sea users. Term of Reference f) Wave and tidal energy must sit harmoniously alongside other stakeholders in the marine environment. Other, more long-standing industries will have lessons for the wave and tidal energy industry in how this is best achieved for the benefit of both stakeholders and the environment. Term of Reference g) ASC in 2011 will include a theme session "Extracting energy from waves and tides – what are the consequences for ecosysmens, physical processes and other sea users?" This SGWTE meeting will be an opportunity to review the science on display at the conference and decide on how best to disseminate it. Term of Reference h) The work of SGWTE intersects with a number of other Expert Groups and the meeting will be an opportunity to integrate input from these groups and regularize interactions.
Resource requirements	The research programmes which provide the main input to this group are already underway, and resources are already committed. The additional resource required to undertake additional activities in the framework of this group is negligible.
Participants	The Group consists of experts in ocean energy resources, environmental and socio economic aspects of marine planning and regulation.
Secretariat facilities	None.
Financial	No financial implications.
Linkages to advisory committees	There are obvious direct linkages with the advisory committees (see last years OSPAR request).
Linkages to other committees or groups	There should be close links with SSGHIE, STIG-MSP, WGMPCZM and several other WGs.
Linkages to other organizations	Needs to be established, OSPAR is interested in this issue.

Annex 4: Recommendations

Recommendation	Adressed to
1. SGWTE recommmends to continue the work of collating information on wave and tidal energy activities and related research by ICES nations (ToR a).	SCICOM, SGWTE
2.SGWTE recommends to compile a publicly searchable bibliography of outputs from state-of-the-art research relating to the environmental and socio-economic impacts of wave and tidal energy developments.	SCICOM, SGWTE
3.SGWTE recommends that ICES encourages member states to support its activities by nominating members to participate in the group.	SCICOM
4. SGWTE recommends a joint ICES-SOWFIA-NERC KEP workshop to address the topic of what we have learned from the wave and tidal energy test sites, and that the output from this workshop should take the form of an ICES Cooperative Research Report. It is suggested that this workshop could be held in conjunction with SGWTE 2012 in Orkney.	SCICOM

Annex 5: Advice to OSPAR on environmental interactions of wave and tidal energy generation devices (extract from ICES Advice 2010, Book 1)

1.5.5.7. Special request Advice June 2010

SUBJECT **Environmental interactions of wave and tidal energy generation devices**

Advice Summary

Renewable energy developments (wave, tidal stream and barrage/fence) are likely to become important features of the OSPAR area. The likely ecological impacts of barrages/fences are large and reasonably well understood, but the impacts of wave, and particularly tidal stream, devices, are much less predictable and have the potential to be significant for some groups of organisms. It is important that the results of thorough monitoring of early deployments of wave and tidal stream devices are published and used to guide the management of subsequent developments.

Request:

Environmental interactions of wave and tidal energy generation devices (Marine wet renewables)

(OSPAR 2010/4)

To provide advice on the extent, intensity and duration of direct and indirect effects and interactions of marine wet renewable energy production (wave, tidal stream and tidal barrage systems) with the marine environment and ecosystems of the OSPAR maritime area, and with pre existing users of these ecosystems, including:

a. actual and potential adverse effects on specific species, communities and habitats;
b. actual and potential adverse effects on specific ecological processes;
c. irreversibility or durability of these effects.

ICES Advice

Tidal barrages will alter tidal processes at the deployment site, and may be detectable over large sea areas. Tidal barrages represent a major modification to the coastal environment impinging on natural processes, and on many maritime activities. The scale of the construction projects for barrages and fences is potentially large and many of the major impacts associated with this phase, for example noise from pile driving, can be mitigated by careful planning, for example by avoiding critical times of year for marine mammals.

The principal environmental effects of a barrage are the changed tidal regime and its impact on bird communities and habitat availability. Many of the sites suitable for use will be designated sites for conservation value. The impacts on bird feeding habitat will be significant if intertidal mud/sand flats are affected. The use of a system that generates power on both ebb and flood tides (dual cycle generation) or the substitution of the barrage by a tidal fence may reduce some ecological effects as the tidal fences are not expected to alter the timing or amplitude of the tides. If the site was on a fish migration route (e.g. salmonids, eels, shad) fish passes need to be provided. Tidal barrages are likely to have a design life of more than 100 years and so effects will be persistent.

i) Tidal stream and wave energy devices are still in the experimental/trial phases and there are no data on the environmental effects of large scale commercial developments. Areas to locate tidal stream devices will be limited by the availability of the tidal resource but could occupy large areas of sea. However, wave energy resource is much more extensive in area than the tidal energy resource. Both technologies have the potential to occupy large sea areas for several decades.

ii) The main ecological concerns regarding tidal stream developments are associated with their potential interactions with wildlife. The effect of the presence of turbines on the behaviour of marine mammals and migratory fish, and the potential for more direct interactions (e.g. collision) with marine mammals, birds and fish have not been well quantified.

Wave energy collectors have the potential to alter water column and sea bed habitats and by changes in the wave environment cause changes some distance from the installation. The effects of wave energy farms are poorly understood, making it hard to prioritize areas of environmental risk. The deployment of wave energy farms will potentially lead to change in benthic and pelagic habitat characteristics with consequential impacts on food web dynamics.

The environmental consequences of the construction and decommissioning of renewable energy projects will have considerable similarities to the consequences of other large scale marine or coastal projects. The processes will involve the operation of heavy lifting barges, increased shipping activity, anchoring, pile driving, construction of caissons, leading to the introduction of noise, vibration, disturbance of the sea bed, resuspension of sediment, disturbance of marine organisms, etc. The mitigation measures used in other contexts will be applicable to renewables, and may include management of the time of construction, noise mitigation measures, the use of marine mammal observers etc.

The installation of electrical transmission cables will entail some disturbance of the seabed and impacts on benthic habitats. Cables will act as sources of electromagnetic fields (EMF), although these will be less strong if paired DC systems are used. There is some uncertainty in the response of marine organisms to EMF, although mitigation measures, such as the use of buried cables, should greatly reduce the risk of significant impacts.

There are some general consequences of marine renewable developments. Their physical presence has the potential to affect utilisation of these areas by other marine sectors, mainly through restriction of access. This restriction has the potential to lead to conflicts with other sea users, primarily fishing and shipping. From a biodiversity point of view, restricted access may have some effects similar to those associated with the developing network of marine protected areas. For some installations, there may not be much visible infrastructure above the water surface, and so hindrance to normal marine navigation will need to be carefully managed. Conversely, their visual impact will be less than that of wind farms.

A recent review of the ecological effects of renewable energy devices in the coastal zone illustrated the sharp increase in the number of peer-reviewed science articles in this area since the early 1990s. However, less than 10% of these articles are related to environmental impacts and even fewer address ecological consequences related to the construction, deployment and decommissioning of renewable energy devices. There is a general paucity of peer-reviewed publications, particularly with respect to tidal barrages/fences, tidal stream and wave energy devices. It is important that appropriate scientific studies should therefore accompany the licensing of the first commercial scale installations, and that these are made available through the open literature. The influence of the development of renewable energy resources (e.g. wind, hydropower, tidal and waves) on marine habitat and biota is one on the priorities of the ICES Science Plan.

iii)

Recommendations

An iterative approach to the management of impacts is needed. As the types of technology develop, the environmental impacts and research needs will become more clear. All opportunities to monitor commercial scale developments should be taken to inform this process.

Basis of advice

The various nations that border the OSPAR region are all committed to significant reductions in CO_2 emissions in the near term. Against this background energy demand continues to grow and restrictions on energy use are likely to be seen as economically and socially damaging. The challenge is therefore to move to a new low carbon economy where energy demands can be met while levels of CO_2 emitted are reduced.

1. Tidal Barrage/Fence[1]

1.1. Habitat change

Building tidal barrages across and within a bay/estuary will destroy the former habitat under the physical structure and modify other areas within the development footprint. The presence of a barrage also influences habitats upstream and downstream of the facility. Upstream, under ebb-only generation, the upper intertidal remains submerged for a longer period; there is then a steady fall in tide level until the tide starts rising again. The former lower shore remains submerged. These changes will shift the balance between marine intertidal species with upper shore specialists potentially being squeezed out. The retention of water also significantly alters the exposure of tidal flats to feeding birds although the resource in the tidal flats when they are exposed may increase in quantity and quality. The availability of alternative feeding/roosting sites is therefore often critical. The implications for tidally feeding fish are the opposite to those of the birds with greater periods for foraging available due to the retention/raising of water levels.

Downstream of the barrage tidal range is often reduced close to the barrage but enhanced in other parts of the basin (Wolf *et al.*, 2009). The outflow will delay the falling

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[1] The request specifically mentions wave, tidal stream and tidal barrage systems. ICES recognises that there are additional technologies that use temperature and pressure differentials, however, the three mentioned in the request are the only ones considered here as these are at the most advanced stage of development. Tidal fences are considered as a variation of tidal barrages. Both these systems can either span across an estuary or can be located so as to utilise tidal flow only.

tide from around mid-tide downward, such that the tide falls as normal, or more rapidly, from high water until the turbines open at mid-tide after which the rate of fall declines or is halted. This has potential negative implications for birds, although this effect occurs as the flats above the barrage become exposed.

Energy generation using barrage systems that generate power on both ebb and flood tides reduces considerably the changes in exposure of the intertidal area and so reduces potential impacts on the bird community. Tidal fences are not expected to alter the timing or amplitude of the tides.

The economics of a barrage or fence scheme scale with the volume of the tidal prism and hence the most favoured schemes tend to involve large estuaries or bays. For example, one option proposed for the Severn barrage in the UK would see 520 km^2 of the estuary impounded, compare this with the 17 km^2 at La Rance and 6 km^2 at Annapolis Royal. Given the very large environmental concerns with Severn development, the smaller Mersey barrage may be the first in the UK to get regulatory approval. The Mersey scheme would involve an impoundment of 61 km^2 but even this would be sufficient to generate changes in the tidal range at locations all around the Irish Sea (Wolf *et al.*, 2009).

Changed spatial flow patterns will result in altered patterns of sediment deposition and movement. These will have impacts on benthic communities. The outflow will be constrained to the locations where the turbines are, and in these areas sediments will be scoured and coarsened while upstream of the barrage the reduced flows and periods of no flow will lead to increased siltation and potentially an increasing quantity of fine material in the deposits.

Changes in the nature of the habitats will alter their suitability as nursery or spawning areas for fish. While some species may benefit from larger areas of appropriate conditions this still represents a deviation from the normal, pre-impact system.

1.2. Water column processes and hydrography

Downstream of the barrage during outflow and immediately upstream on inflow, the constraining of the flow will lead to turbulent flows that will increase mixing. Upstream for much of the tidal cycle the water in the basin will be fairly static and this could lead to stratification, and changes in the phytoplankton dynamics.

In the Severn Estuary, for example, the strong tidal flows lead to highly turbid conditions and hence low primary productivity. Underwood (2010) suggested that following construction of a barrage the increased water clarity upstream could lead to increased phytoplankton derived primary production. However, this is thought to be less than the loss of primary production from microbial primary producers in the sediments due to the impounding of water and the reduction in the emergent area of the tidal flats.

Studies of the impact of passage through turbines on marine plankton are currently lacking. Reported mortality of freshwater zooplankton following entrainment in hydroelectric turbines can be high (Jenner *et al.*, 1998). However, in many estuaries where tidal ranges are large plankton populations are low and derived from individuals advected into the estuary. This suggests that even if mortality of entrained individuals is high this is not likely to be significant at the population and community level.

Levels of direct mortality of fish passing through high-speed turbines can be high and the disorientation caused may lead to lowered ability to avoid predation in the period after passage. These fish will include both migratory species as well as those that move into shallow waters to feed and/or reproduce. However, there is considerable experience of engineering sluices, cooling water intakes and turbines to reduce fish entrainment (Coutant and Whitney, 2000) and such mitigation measures should be seen as a critical part of any system design.

Energy extraction may affect turbulent mixing, and change patterns of sediment distribution. Tidal fences in high energy coastal areas may encounter currents moving at 5 to 8 knots (9 to 15 km per hour) producing intense mixing processes continuously in the water column. At lesser velocities some degree of water column stratification can be expected (Gray, 1992). This may also bring increased water clarity through reduced sedimentation.

1.3. Spatial interactions with pre-existing users

The presence of the barrage or fence will have an impact on existing uses such as fishing, aquaculture, navigation, recreation and seascape and these could be both positive and negative and in some cases provide new opportunities. The necessity for exclusion zones will depend on the location, the device and the activity. On most large barrage proposals spanning an estuary the passage of shipping through the barrage is maintained by the provisions of appropriate lock systems with associated breakwaters and channels.

Exclusion zones will be required during both construction/decommission and operation phases. These zones would likely be larger during the construction period and reduced once the system was operational.

1.4. Noise

Possible effects on marine mammals include noise and vibration during operation affecting species that use sonar to pursue prey or affecting communication between animals; direct collision or contact; and indirect effects on the distribution and abundance of prey species. Overall, operational noise of tidal barrages/fences is unlikely to be ecologically significant unless the area is intensively used by marine mammals.

1.5. Food chain

The principal food chain effect of tidal barrages is the reduction in availability of infaunal food to the bird population. In the UK, and probably northern Europe in general, the quantity and quality of the food on the feeding grounds of over wintering waders determine survival to the next breeding season. Thus reduced feeding areas, increased foraging costs (extra flights between sub-optimal grounds) or lower food quality will directly impact on population size. The greater foraging time available to fish predators in the intertidal may also alter species composition of the fish assemblage by favouring species able to exploit this resource efficiently, but the consequences in individual cases are difficult to predict. Food chain effects produced by tidal fences are expected to be much less.

1.6. Reproduction

Locating a barrage on or near a nursery or spawning area will clearly have an impact. These are site specific considerations. More generally by producing a barrier across the estuary/fjord the barrage will impact on migrations of anadromous and catadromous species including economically important salmonids and eels and protected species such as shad.

Tidal fences will also restrict fish and marine mammal passage through physical blockage, although there is room for mitigation through engineering of the fence structure to allow spaces for fish to pass through between the caisson wall supporting the turbines and the rotors. Further, placement of the fence (in-parallel or in-series to water flow) can greatly influence impacts on species and habitats.

2. Tidal Stream Farm

2.1. Habitat change

Energy generation using the tidal stream uses turbines or other devices placed in the water column to extract energy. The installation and operation of individual or multiple tidal stream devices, as with other forms of wet renewable energy systems, directly affect benthic habitats by altering water flows, wave structures, or substrate composition. Physical impact from small-scale tidal stream generation pilot projects have been found to be reversible on decommissioning, especially as the areas most suitable for tidal power generation are located where high current flow causes natural disturbance to the sediments. However, the cumulative effects of multiple turbines also need to be considered with respect to far field impacts.

Installation will alter benthic habitats over the longer term if trenches containing electrical cables are backfilled with sediments of different size or composition than the previous substrate. The use of large particles as a cover may be required to reduce the likelihood of cables becoming exposed and emitting electromagnetic fields into the water column.

When operational, regardless of design and size, all tidal stream farms will include a large anchoring system made of concrete or metal, mooring cables, and electrical cables that lead from the offshore facility to the shoreline. Electrical cables may simply be laid on the bottom, or more likely anchored or buried to prevent movement. Movements of mooring or electrical transmission cables along the bottom (sweeping) have been shown to be a continual source of habitat disruption during operation. The strumming action of cables has been shown to cause incisions in rocky outcrops, but effects on seafloor organisms have generally be shown to be minor (Kogan *et al.*, 2006). Large bottom structures will alter water flow and may result in localized scour and/or deposition. Because these new structures will affect bottom habitats, consequential changes to the benthic community composition and species interactions may be expected (Lohse *et al.*, 2008).

Mobile bedforms resulting from the effects of new installations could modify the benthic habitat nearby, though the extent of these modifications depends on the character of the bottom in question. Tidal stream farms will likely be located in dynamic areas of exposed bedrock, which could reduce downstream drifting of sediment.

At this time, there are insufficient data to state definitively how fish and fish habitat will be impacted by the operation of tidal stream power projects. No published data on the interactions between turbines and fish in the marine environment could be found except for some information from the Roosevelt Island tidal energy project in New York city’s East River (Anon, 2008). That study showed that densities observed in and around the turbines were generally low (range of 16–1400 fish per day seen); the fish were predominantly small but still swam faster than the turbines rotated; and fish movement tended to be restricted to the direction of the tide and during slack water when the turbines were non-operational (Anon, 2008).

There remain large information gaps concerning the collision risk of marine mammals with structures such as tidal stream farms (but see SeaGen, 2009). The literature reviewed suggests that the probability of cetaceans failing to detect and avoid a large static structure is considered to be extremely low, particularly for species that echolocate and are agile and quick moving. The exact placement of tidal farms for species that frequent particular areas, either through site fidelity or seasonally, should be considered in mitigation. Feeding and breeding sites in particular for marine mammal species should be avoided when tidal farm sites are selected. This is logical risk management strategy in the face of uncertainty even though there are no documented cases of any negative impact on marine mammals.

The impacts of tidal stream farms on seabirds are also reported to be small (e.g. Anon, 2008). Risk of collision is expected to be minimal as for many species of sea birds, including gulls, terns, kittiwakes, fulmars and skuas, their normal depth range would not allow them to encounter operating turbines. For some deep diving species, e.g. auks, shags, there is the chance of an encounter as these species regularly dive to depths of 45–65m. The critical issue is the relative swimming speed of the bird, and the ability to sense and respond to the turbine. It is thought that the slow turbine speeds relative to the agility of diving bird species would make the risk of mortality very low (Awatea, 2008). However, a typical swimming speed for these species is of the order of $1.5ms^{-1.}$. For comparison, the tip turning at 15rpm would be moving faster than this and so potentially be difficult for a bird to avoid. The possible interactions are further complicated by the possibility that diving birds may respond to the moving blades as potential prey and be attracted to their vicinity. Further work is needed to elucidate the scale of this phenomenon and to develop mitigation measures, i.e. painting the blades.

There is a lack of information on the interaction of marine mammals, fish and birds and the moving parts of tidal stream devices. The risk of collision with the moving parts of turbines is dependent on a wide range of factors, including the ability of organisms to detect and avoid them. However, while some bird species appear to dive and feed at all states of the tide, there are field observations that suggest that seals may tend to congregate in near-shore, relatively quiescent, areas at times of maximum tidal flow when turbines will be operating at full capacity and thereby reduce their risk of collision.

2.2. Water column processes and hydrography

Tidal energy power generation devices have the potential to increase turbulence in the water column, which in turn will alter mixing properties, sediment transport and, potentially, wave properties. In both the near field and far field, extraction of kinetic energy from tides will decrease tidal amplitude, current velocities, and water exchange in a region in proportion to the number of units installed, potentially altering hydrography and sediment transport. The effect on transport and deposition of sediment may also influence organisms living on or in the bottom sediments, and plants and animals in the water column. Moving rotors and foils have been shown to increase mixing in systems where salinity or temperature gradients are well defined.

Changes in water velocity and turbulence will vary greatly, depending on distance from the structure. For small numbers of units, the changes are expected to dissipate quickly with distance and are expected to be only localized; however, for larger commercial arrays, the cumulative effects will extend to a greater area although it is still not known whether these would have significant effects on the ecosystem.

Tidal energy turbines may also modify wave heights by extracting energy from the underlying current. The effects of structural drag on currents are not expected to be significant (MMS, 2007), but few measurements of the effects of tidal/current energy devices on water velocities have been reported.

Changes in water velocities and sediment transport, erosion, and deposition caused by the presence of new structures will alter benthic habitats, at least on a local scale. Craig *et al.* (2008) reports that deposition of sand may impact seagrass beds by increasing mortality and decreasing the growth rate of plant shoots. While the new habitats created by such structures may enhance the abundance and diversity of invertebrates, predation by fish attracted to artificial structures can greatly reduce the numbers of benthic organisms (Davis *et al.*, 1982; Langlois *et al.*, 2005).

2.3. Spatial Interactions with pre-existing users

It is likely that tidal stream farms may have exclusion zones within and around them to provide a safety barrier from other activities, such as fishing and navigation (depth dependent), similar to those found at other marine energy structures. Exclusion zones are likely to be marked by cardinal buoys and navigation lights, noted on shipping charts in future and advised through Notices to Mariners. Whilst other human activities are likely to be excluded in the area of marine energy converters arrays, the resultant exclusion zones may create *de facto* marine reserves, in which marine life can flourish. The nature of the changes associated with these closed zones is not simple to predict but there is a considerable body of data showing the effects of such schemes (Balmford *et al.*, 2004; Murawski, 2005; Murawski *et al.*, 2005; Kaiser, 2005; Rice, 2005). They may lead to fishery displacement to other areas. Marine energy projects will add to the cumulative impact of closures for other reasons.

2.4. Noise

There are considerable information gaps regarding the effects of operational noise generated by tidal stream farms on cetaceans, pinnipeds, turtles, and fish. Sound levels from these devices have not been routinely measured, but it is likely that installation will create more noise than operation. Operational noise from generators, rotating equipment, and other moving parts may have comparable frequencies and magnitudes to those measured at offshore wind farms; however, the underwater noise created by a wind turbine is transmitted down through the pilings, whereas noises from tidal stream farms are likely to be greater because they are at least partially submerged. Operational noise from a small number of units may not exceed threshold levels, but the cumulative noise production from large numbers of units has the potential to mask the communication and echolocation sounds produced by aquatic organisms in the vicinity of the structures.

Resolution of the significance or otherwise of noise impacts will require information about the device’s acoustic signature (e.g. sound pressure levels across the full range of frequencies) for both individual units and multiple-unit arrays, similar characterization of ambient noise in the vicinity of the farm, the hearing sensitivity of fish and marine mammals that inhabit the area, and information about behavioural responses to anthropogenic noise (e.g. avoidance, attraction, changes in schooling behaviour or migration routes).

2.5. Food Chain

Principal indirect effects of tidal power turbines will relate to the consequences for biota of local physical impacts, and to changes in hydrographic conditions that may result from tidal energy extraction. Few studies have been undertaken which help to specify the magnitude or importance of such effects, beyond those generic indirect effects resulting from the placement of structures on the seabed.

Numerical modelling methods are available to predict the effects of developments on stratification and mixing in the water column. Some consequences for primary production and larval settlement may be predicted, but are likely to be localised. Alterations in patterns of turbulence may affect the feeding behaviour of some seabirds, particularly terns.

2.6. Reproduction

In general reproduction of species is unlikely to be affected by these devices.

3. Wave Energy Farm

3.1. Habitat and Species

Wave energy farms show a wide variety of systems, at several stages of development, competing against each other, without it being clear which types will be the final winners (Falcão, 2010).

The dampening of waves may alter coastal processes affecting the balance between erosion and deposition of sediments; this may have both societal and environmental impacts. Dampening may cause ecological changes but sheltering due to wave devices will have a negligible effect on the largest waves (Pelc and Fujita, 2002).

Some offshore wave energy farms are expected to contribute to an increase in submerged constructions on the seabed, including a possible impact on the surrounding soft-bottom habitats. As both pilot and commercial wave energy converting applications are limited, so are studies on habitat change. Langhamer and Wilhelmsson (2009) examined the function of wave energy foundations as artificial reefs. Langhamer *et al.* (2009) demonstrated that foundations serve as colonisation platform with a higher degree of coverage on vertical surfaces.

Regarding the pelagic habitat, buoys have positive effects on forage species, which consequently cause an attraction of large predators. On the other hand, lines on structures can cause the entanglement of marine mammals, turtles, larger fish and seabirds, but they also can produce an increase of settlement of meroplankton (Boehlert *et al.*, 2007; DFO, 2009). The pelagic habitat is also changed by creating platforms for predators, e.g. seabirds, and by changing the hydrographical conditions.

3.2. Water column processes and hydrography

Wave power plants act as wave breakers, calming the sea, and the result may be to slow the mixing of the upper layers of the sea, which could cause an adverse impact on the marine life and fisheries (Pelc and Fujita, 2002). The energy devices remove energy from the wave train, affecting the height of the splash zone, sediment deposition and ecosystem productivity. Similarly, erosion patterns along long stretches of coastline could be changed, being the effect beneficial or detrimental depending on the specific coastline (Pelc and Fujita, 2002). They may also modify some other local sediment transport patterns (including re-suspension and deposition) by localized hydrodynamic changes due to presence of physical structures and from energy extraction. Depending on the location, scale, technological characteristics and dynamical processes, all these effects can be extended along the environment. Substrate disturbance during deployment, decommissioning and maintenance processes, for example, can lead to increased suspended sediments and turbidity, especially in areas with finer substrates such as sand or silt. Sediment re-suspension may directly cause deleterious health effects or mortality to fish, and increased turbidity could hinder the prey detection ability of species that rely on visual cues (DFO, 2009). All these processes could alter the way the ocean interacts with the atmosphere locally but given the scale of the ocean they are unlikely to be of ecological significance for system functioning (Pelc and Fujita, 2002).

3.3. Spatial interactions with pre-existing users

Commercially operated wave energy farms are limited (e.g. Portugal and Scotland). Therefore, one can only speculate about possible configurations (e.g. Falcão, 2010). Length and width vary by number and type of Wave Energy Converters (WECs) with single devices ranging from 15 to 150 m. However, WECs are usually deployed in multiples and the footprint will therefore vary with the actual configuration. There is more likely to be navigation exclusions related to the surface positioning of these devices. However fisheries and recreation activities may also be affected.

3.4. Noise

A large number of species of different taxa (cetaceans, pinnipeds, teleosts, crustaceans) use underwater sounds for interaction and echolocation (Misund and Aglen, 1992; Popper and Hastings, 2009; Langhamer *et al.*, 2010). There have been very few (if any?) directed studies of the response of fish and marine mammals to noises and vibrations produced by operational WECs, (DFO, 2009). DFO (2009) reports existing modelling studies suggesting construction and operation noise levels can cause temporary, or in certain circumstances, permanent hearing loss in porpoises, seals and some fish and interfere with interactions between organisms (communication, finding prey, location of recruitment sites, etc.). As for other effects, the type of WECs and scale of application determine the production of noise and subsequent effects (Boehlert *et al.*, 2007). The constant low-intensity sounds from operating WECs have also been compared to low /normal density shipping noise or noise generated from a ferry (Anon, 2008), implying that effects may also be of a comparable magnitude.

3.5. Food Chain

Wave energy arrays provide a matrix of hard structures which will likely have ecological consequences from the fouling community up through the highest levels of trophic structure. Moreover, forage species are attracted by these devices, which is associated with an increase of presence of large predators and the corresponding changes in the food web.

Some marine species (cetaceans, pinnipeds, teleosts, crustaceans) are especially sensitive to acoustics (Popper and Hastings, 2009). Avoidance of areas by certain species or changes in foraging success due to interactions between anthropogenic noise with acoustic sensory apparatus could result in food chain effects (Boehlert *et al.*, 2007). The structural complexity that these devices give to the marine environment will alter the habitat and hence the trophic relationships. For example, they provide opportunities for ambush predators as well as shelter for prey and the presence of organisms attached to or hiding between the structures may serve to increase the range of potential prey items available (Langhamer *et al.*, 2010). Field evidence for these processes is currently lacking.

Some authors have speculated that changes in surface productivity linked to a reduced mixing may alter the food supply to benthic populations (Pelc and Fujita, 2002). Models are available to predict the extent to which wave energy farms will reduce water column mixing or the amplitude of waves impinging on to coastal habitats.

3.6. Reproduction

It has been hypothesised that noise might interfere with the ability of some fish species that locate their nursery areas by sound (Langhamer *et al.*, 2010) although specific data were not presented. Breeding vocalizations are important for mate attraction in freshwater goby (Lugli *et al.*, 1996), cod (Finstad and Nordeide, 2004) and haddock (Hawkins and Amorima, 2000).

4. Generic

4.1. New hard surfaces

Permanent structures on the bottom (ranging in size from anchoring systems to seabed-mounted generators or turbine rotors) will smother existing habitats. These new structures would replace natural hard substrates or, in the case of previously sandy areas, add to the amount of hard bottom habitat available to benthic algae, invertebrates, and fish. This could attract a community of rocky reef fish and invertebrate species (including biofouling organisms) that would not normally exist at that site. It has been speculated that depending on the location, the newly created habitat could increase biodiversity or have negative effects by enabling introduced (exotic) benthic species to spread. Marine fouling communities developed on monopiles for instance in offshore wind power plants have been found to be significantly different from the benthic communities on adjacent hard substrates (Wilhelmsson *et al.*, 2006; Wilhelmsson and Malm, 2008).

4.2. Cables including Electromagmetic Fields (EMFs)

The environmental impacts of electromagnetic emissions from cables, switch gear and sub-stations is the same irrespective of the energy generating device and thus the lessons learnt from offshore wind power developments are applicable to developments harnessing tidal stream or wave energy.

It is well documented that several marine species use magnetic and electrical fields for navigation and locating prey. Electrical fields (E fields) are proportional to the voltage in a cable, and magnetic fields (B fields) are proportional to the current. All fish are sensitive to a greater or lesser extent to electric fields. The background document working group report (ICES, 2010a) provides details on the available knowledge of these effects on a number of fish species and expands on the information listed in the OSPAR background document on cables (OSPAR, 2009).

Cables carrying direct current (DC) from individual installations are likely to carry only 10–15 kV, which is unlikely to generate any electrical field more than a few centimeters from the cable (Westerberg and Begout-Anras, 2000).

Langhamer *et al.* (2009) remarks that with the use of a better cable technology the electromagnetic fields only affect the nearest surroundings as the background earth magnetic field usually becomes more prominent only a few decimetres from the cable. In combination with cables buried into the seabed, issues with electromagnetic fields might disappear.

Electricity generated by the existing barrage facilities is carried away by cables running on the top of the barrage and so has no marine environmental impact.

5. Contaminants and anti-fouling

With regard to water quality, the loss of oil is the biggest impact identified. Subsurface electrical equipment will contain oil as an insulator and lubricant while some designs of wave and tidal stream energy collection devices use hydraulic systems that will contain oil. Modular design and appropriate valves should limit the volume of oil loss in the event of a structural failure or collision damage (Boehlert *et al.*, 2007). Modern materials used in manufacturing and the regulations regarding placement in the marine environment will limit the risk of the devices introducing contamination into the sea (Boehlert *et al.*, 2007; DFO, 2009).

One potential source of contamination is leaching from anti-fouling preparations. Modern anti-fouling preparations tend to be low in toxicity and biodegradable.

6. Construction and Decommission

The environmental consequences of the construction and decommissioning of renewable energy projects will have considerable similarities to the consequences of other large scale marine or coastal projects. The processes will involve the operation of heavy lifting barges, increased shipping activity, anchoring, pile driving, construction of caissons, leading to the introduction of noise, vibration, disturbance of the sea bed, resuspension of sediment, disturbance of marine organisms, etc. The mitigation measures used in other contexts will be applicable to renewables, and may include management of the time of construction, noise mitigation measures, the use of marine mammal observers etc.

Activities likely to produced noise at levels of concern include pile-driving, explosive or seismic work. Even within the construction/decommissioning phases these are intermittent, short duration activities but they have the potential to effect cetacean or pinniped activity in the region at the same time (Madsen *et al.*, 2006). At offshore wind farms in Denmark, Henriksen *et al.* (2004) and Tougaard *et al.* (2003) both found effects on the behaviour and abundance of harbour porpoises during pile driving activities. Fewer animals exhibited foraging behaviour and there was a short-term reduction of echolocation activity. These effects were documented up to 15 km from the impact area. These effects were, however, short-lived once construction ceased (Carstensen *et al.*, 2006). Studies suggest that high-level impulsive sounds have a greater effect on cetaceans than pinnipeds (McCauley and Cato, 2003; Gordon *et al.*, 2004). Langhamer *et al.* (2010) remark that the production of noise by drilling and placing during construction, cable laying, as well as boat traffic can damage the acoustic system of species within 100m from the source and cause mobile organisms to avoid these areas during that time.

During construction noise and vibrations would affect different fish species in different ways (US Department of Energy, 2009; DFO, 2009). Pile driving would likely affect schooling fish or any species with a swim bladder. Effects on other species would be less certain. Effects could be direct, by damaging sensory or sensitive tissues, or indirect, by changing behaviours. Migratory shorebirds depend on benthic intertidal invertebrates, the abundance and distribution of which might be altered by tidal development through sediment changes. During the operations phase noise and vibrations could continue to affect some species. It is important when assessing noise effects that the cumulative effects of the entire system be evaluated and not just the levels produced by individual modules (US Department of Energy, 2009).

During the construction phase of tidal stream farms the impacts on habitats will be similar to those experienced in the construction of other wet renewable installations.

Bottom disturbances will result from the temporary anchoring of construction vessels; digging and refilling the trenches for power cables; and installation of permanent anchors, pilings, or other mooring devices. Fish and other mobile organisms will be displaced and sessile organisms smothered in the limited areas affected by these activities. Species with benthic-associated spawning or whose offspring settle into and inhabit benthic habitats are likely to be most vulnerable to disruption during installation. The general mitigating considerations applied to marine construction should also be appropriate to wet renewables.

Temporary increases in suspended sediments and sedimentation down stream from the construction areas can also be expected. When construction is completed, disturbed areas are likely to be re-colonized by these same organisms, assuming that the substrate and habitats are restored to a similar state (e.g. Lewis *et al.*, 2003).

Consistent with other marine construction projects detailed site investigations including baseline monitoring and archaeological surveys are needed.

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Annex 6: Working paper - Environmental impacts of tidal and wave power developments and key issues for consideration by environment agencies

Background Report on Task 2 of Sniffer ER20: Tidal Technologies: Key issues across planning and development for environmental regulators

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1. Introduction

Renewable energy technologies are commonly seen as a panacea for the environmental problems associated with power generation, not just in terms of greenhouse gas emissions but also by virtue of other impacts such as pollution and habitat destruction (e.g. Dincer 1999). This may well be true of wave and tidal energy developments, but the fact is that there are few direct observations from which to judge the nature and scale of impacts. This is partly because of the emergent state of the industry, but also because research into this field has tended to focus on the nature of the resource and on the engineering aspects of exploiting it rather than on the environmental consequences of such exploitation.

This is not to say that there is *no* evidence base from which to draw inferences on the *potential* for wave and tidal energy developments to impact upon the marine environment. Information from impact studies of other human activities provide valuable insights into how some aspects of power generation may interact with the environment. Coupled with knowledge about the vulnerabilities of particular species and habitats and about the inter-relatedness of physical and ecological processes, this information provides at least a starting point for understanding the likely consequences of marine energy extraction for the physical and biological milieus in which it is placed. A number of recent reviews (e.g. Gill 2005, Inger *et al.* 2009, ICES 2010a, 2010b, Shields *et al.* 2011) have drawn together much relevant information for a qualitative appreciation of the perceived potential for environmental interactions involving marine renewable energy developments. Several types of interaction may be distinguished:

- energy extraction impinging upon natural processes;
- operational effects on marine biota, acting through device operation, maintenance and decommissioning;
- provision of new ecological space through the physical presence of devices and other development structures;
- displacement of other human activities, modifying the locus and nature of their impacts.

The least attention has so far been paid to the first of these aspects, particularly in terms of intervention in physical processes. For this reason, this document places particular emphasis on the previously under-reviewed topic of potential impacts on physical processes, the more so because many other potential impacts stem from the physical impacts as first causes. We pull together the first comprehensive review of the potential for wave and tidal energy extraction to impinge upon physical processes in the near- and far-fields of developments, before going on briefly to examine the implications for ecological processes. Operational effects are considered mainly in terms of noise and collision risk; pollution risk involving release of oil and chemicals is probably fairly low, and is a general risk for human activities at sea rather than being particular to wave and tidal energy extraction. Changes to ecological space are considered in terms of reef effects and structures functioning as fish aggregation devices. Finally, we focus on marine fishing as the principal interaction with other sea users that is likely to have environmental implications.

2. Physical processes

Generation of power using wave and tidal devices involves interception of hydrokinetic energy that would otherwise be expended elsewhere in the marine environment. This interruption in the 'natural' dynamics of marine energy will inevitably have consequences for other physical processes and for ecological processes and human activities that are influenced by or depend upon the functioning of the physical environment. The scale of physical impacts is likely to depend principally on the amount of energy extracted rather than the method of extraction (Ian Walkington, POL, pers. comm.), although of course device types will differ in the nature of impacts incurred by their operation.

2.1. Tidal energy

Commercially operational tidal energy devices currently amount to a global total installed capacity of 267 MW, with a further 254 MW under construction (List of tidal power stations, 2011). However, only 0.4% of this capacity relates to tidal stream power generation, the single commercial development of this type being the SeaGen turbine installed in Strangford Lough in 2008 with a capacity of 1.2 MW. The remaining 99.6% of capacity relates to tidal barrages extracting energy from differences in water level, the first such development being built in 1966 at La Rance in France (240 MW). It is thus not surprising that there is a lack of practical evidence of physical changes resulting from extraction of energy from tidal currents. Prototype scale models of tidal stream devices are installed for sea trials at various locations, notably the EMEC tidal energy test site at the Falls of Warness, Orkney (EMEC 2011), but limited information on environmental effects has so far emerged from these trials.

At this early stage of development of in-stream tidal power generation, hydrodynamic modelling studies provide the best source of information on the likely consequences of device operations, particularly at commercial scales. Many modelling studies are aimed principally at quantifying the tidal stream resource (e.g. Blunden & Bahaj 2006, Bryden *et al.* 2007, Carballo *et al.* 2009), but increasingly tidal energy extraction devices are explicitly included in models, simulated as increased bottom drag (Sutherland *et al.* 2007, Walkington & Burrows 2009) or non-linear drag forces associated with the presence of turbines in a channel (Garrett & Cummins 2008, Karsten *et al.* 2008). Given that in-stream tidal power generation involves extraction of hydrokinetic energy, the overall effect of devices must be to decrease average water velocity. Bryden *et al.* (2004) pointed out that reductions in flow speed, and hence energy flux, will place limits on the amount of energy that can be extracted from a channel, and that estimates of available energy should take account of flow reductions rather than being based only upon undisturbed flow. They suggested that for a simple channel a 'rule of thumb' limit for environmentally acceptable energy extraction could be 10%, for which a flow speed reduction of less than 3% would be expected (see also Bryden & Couch 2006). However, they also noted that in practice the hydraulic domain of real-life cases is likely to be much more complicated than an idealised simple channel, and correspondingly more complex flow analysis would be needed to determine appropriate limits for extraction of energy from tidal flow. In real-life cases there also needs to be some consideration of how waves interact with currents. In shallow water areas of significant wave action, shear forces experienced at the seabed may be considerably more affected by waves than currents, such that reductions in current speed may have lower than anticipated effects on seabed hydrodynamic conditions. This topic merits further research, particularly in relation to the effects of tidal energy extraction on benthic communities.

Walkington & Burrows (2009) used the two-dimensional depth-integrated ADCIRC model (Hench & Luettich 2003) to simulate tidal flow in a large spatial domain west of the UK. They examined tidal stream energy extraction at four locations on the west coast of England and Wales with rated capacities varying from 8 to 30 MW, and topography varying from flow around headlands to estuarine channel flow. In each case the model indicated a redistribution of tidal flow speeds, with significant decreases (up to 0.2 $m.s^{-1}$) in the immediate vicinity of the tidal farm locations and increases (up to 0.1 $m.s^{-1}$) in parallel flows on either side (baseline flow conditions not stated, but device rated speed was 2.0-2.4 $m.s^{-1}$). These findings mirrored their simulations of an idealised estuary, in which extraction of energy caused a redistribution of flow from the central fast current towards the walls of the channel. These simulations also showed both increases and decreases in flow within the inner estuary and at the estuary mouth, depending on the design of the tidal farm (single or multiple rows of devices, partial or complete channel width). Under one scenario (multiple rows, complete width) there was a reversal of residual current direction within the tidal farm, leading to areas of relative convergence at this location. The importance of these changes in current are that they would be likely to affect near-field (metre to kilometre scale) sediment transport and erosion processes around the tidal energy developments. Increases in flow speed would result in increased scour and, in channels, increased bank erosion, whereas decreases in flow speed would result in increased sedimentation, particularly in areas of convergence of residual currents.

The results of Walkington & Burrows (2009) relate largely to near-field effects of tidal energy extraction, although a small phase shift in the principal lunar semidiurnal (M_2) tidal component was also noted that affected the entire Mersey river. Given the small scale of extraction (total rated capacity 69 MW, annual energy extraction 127 GWh) substantial far-field effects would not be expected. Couch & Bryden (2007) simulated mesoscale effects of tidal energy extraction, demonstrating significant reductions in flow speed with downstream effects at peak tide conditions extending as much as 10 km. Shapiro (2010) considered much larger-scale changes in circulation consequent on removing tidal energy at an offshore location to the north of Cornwall. He used the POLCOMS three-dimensional model of ocean circulation (Holt & James 2001) applied to the Celtic Sea and Bristol Channel, including forcing due to wind stress, temperature and salinity gradients, and water column and bottom stress in addition to tides. At high rates of energy extraction the model indicated changes in current speed and kinetic energy, greatest inside the 12 km diameter of the farm area and within 10–20 km of the farm. Larger scale circulation was also affected, with alterations in residual current patterns at distances of up to 100 km. Similar to Bryden *et al.* (2004) and Garrett & Cummins (2008), Shapiro (2010) highlighted the slowing of currents by frictional forces within the tidal farm. The implications for reduction of energy flux relative to the undisturbed state appear to be even greater in the open shelf sea than in a tidal channel, such that a 'high power' farm rated at one hundred times the power of a 'low power' farm saw only a seven-fold increase in energy extracted – extractable energy fourteen times lower than if the currents were undisturbed.

Sutherland *et al.* (2007) applied the two-dimensional TIDE2D model (Walters 1987) to simulating tidal stream energy extraction in the Johnstone Straits, Vancouver Island, Canada. In this case the main far-field effects were changes in tidal elevations, with extraction of 1.3 GW causing decreases in the amplitude of the M_2 tide of 15 cm in the Strait of Georgia and both increases and decreases in amplitude elsewhere. Impacts on tidal amplitude were found to be linearly related to the scale of energy extraction, with lower levels of extraction yielding proportionately lower impacts. Karsten *et al.* (2008) also identified a trade-off between levels of in-stream tidal power extraction in the Bay of Fundy, Canada, and changes in tidal amplitude. These authors used the two-dimensional FVCOM model (Chen *et al.* 2006) to show that constriction of flow through the Minas Passage by energy extraction would push the entire Bay of Fundy – Gulf of Maine system closer to resonance with the forcing tides, resulting in increased tidal amplitudes throughout the Gulf of Maine – up to 25 cm in the western Gulf of Maine at maximum power extraction. These far-field effects of up to 15% increase in tidal amplitude at 7 GW power extraction would be decreased to less than 5% at an extraction level of 2.5 GW.

The Bay of Fundy is perhaps a special case by virtue of the system being already close to resonance with the forcing tides. The closest analogue in UK terms would be the Severn Estuary, where resonance also plays an important role in determining the large tidal range. Nevertheless, the Karsten *et al.* (2008) study is illustrative of the potential scale of impact from upscaling tidal energy extraction from MW to GW scales. Comparable simulations of GW scale in-stream tidal energy extraction are not available for UK waters, but consideration of tidal range energy extraction may be informative. Tidal barrages are outside the scope of this review, but, as already noted, the scale of impacts is likely to relate largely to the amount of energy extracted rather than the method of extraction. In this context it is worth noting that the results of Karsten *et al.* (2008) relating to in-stream tidal energy extraction in the Bay of Fundy are qualitatively and quantitatively comparable to barrage effects for the same area. Wolf *et al.* (2009) modelled the effects of tidal barrage schemes on five major estuaries on the west coast of the UK, finding significant changes in tidal amplitude (increases of 20 cm) affecting the coast of Northern Ireland and decreases in bed stress, particularly in the Bristol Channel. Effects on tidal mixing might also be expected, although no significant changes in the locations of tidal fronts were evident under the operational scenarios considered. The installed capacity under these simulations was 22 GW, with annual energy extraction of 33 TWh out of a tidal resource of 128 TWh (Burrows *et al.* 2009). This is more than 260 times the 127 GWh annual in-stream tidal energy extraction modelled for the same spatial domain by Walkington & Burrows (2009), for which the far-field effects were negligible.

Three urgent needs may be identified in relation to the interaction of in-stream tidal energy extraction with physical processes, and the potential environmental consequences therefrom. First, there is a need for modelling of upscaled tidal energy scenarios that explicitly consider extraction of energy from tidal currents rather than ranges. Studies such as that of Wolf *et al.* (2009) for tidal barrages are indicative of the potential scale of impacts, but cannot be used to draw detailed inferences or quantitative predictions on the consequences of in-stream energy extraction.

Second, there is a need for site-specific models to cover areas of potential tidal energy exploitation. Simple idealised models, such as those of Bryden *et al.* (2004) and Couch & Bryden (2007) are very useful in identifying issues, and models for particular areas, such as those for the west coast of the UK by Walkington & Burrows (2009), can also be very informative about the types and scales of environmental changes that might be expected under different circumstances, but neither approach can substitute for site-specific models that consider the local complexities of hydrodynamics and other physical processes. In general, such models need to cover large spatial domains, given that energy extraction interacts with large-scale hydrodynamic processes, and also to consider fine-scale processes operating in the vicinities of tidal farms. Site-specific modelling scenarios also need to go beyond single development simulations, since, particularly for upscaled energy extraction, it is likely that the effects of multiple developments will be interactive rather than simply additive, and the effects of energy extraction on the available resource must be addressed. In this context, it is worth noting that the three-dimensional SUNTANS model (Fringer *et al.* 2006) is currently being applied to the Pentland Firth and adjacent waters by scientists at ICIT (Heriot-Watt University). This is an unstructured grid model that allows the appropriate levels of spatial resolution to combine both large-scale processes and near-field effects. Other models, for example using the MIKE 21 modelling package (Warren & Bach 1992), are also being applied to areas of the Pentland Firth and Orkney waters by scientists at EMEC and ERI.

The third obvious research gap is the lack of information on the environmental implications of local wake structures generated by interaction of water flow with turbine blades and support structures. Studies such as those of Couch & Bryden (2007), Walkington & Burrows (2009) and Shapiro (2010) have concentrated on the effects of energy extraction at meso- to macroscales, without explicit consideration of device-scale hydrodynamic interactions. Measurements in test tanks and fluid dynamics modelling may be used to investigate the performance and hydrodynamic properties of specific devices, and results may inform device design and spacing within arrays (e.g. Bai *et al.* 2009, Harrison *et al.* 2009, Myers & Bahaj 2009), but these findings have not yet been taken forward into studies of environmental impacts. Device design is likely to have a strong bearing on the nature of near-field environmental changes, affecting seabed scour, water column structure and sedimentation. It is easily conceivable, for example, that turbulent wakes from tidal devices (e.g. Gant & Stallard 2008, Maganga *et al.* 2010) could have a strong influence on the local vertical mixing processes that are so crucial for trophic coupling in shallow seas and that play an important role in defining foraging habitat for top predators in these environments (Scott 2007, Scott *et al.* 2007).

2.2. Wave energy

There is less information about waves than tidal currents with regards to the potential environmental consequences of extracting energy. The recent state of the art with respect to harnessing wave energy resources is summarised in Cruz (2008). Tentative guidelines for environmental impact assessment are outlined by Huertas-Olivares & Norris (2008), but these are based on expert opinion on potential issues rather than direct experience (see also EMEC 2008). Various reviews have scoped the potential environmental and ecological impacts of wave energy devices and the implications for environmental impact assessment needs (e.g. SNH 2004, Boehlert *et al.* 2008, Linley *et al.* 2009). As with the tidal current devices, the lack of physical evidence is due largely to the nascence of the technology and its deployment. At present there are demonstration scale wave energy devices installed in various parts of the world, with the forthcoming installation of three Oyster 2 devices at the EMEC wave test site in 2011 set to have the highest operational rating at 2.5 MW (Aquamarine Power 2011). The Wave Hub offshore facility off south-west England has capacity for up to 20 MW of installed devices (Wave Hub 2011) and there are projects underway for developments of up to 100 MW off Portugal, Australia and the Pacific coast of the USA (see summary in Linley *et al.* 2009).

Waves and their interactions with structures in the marine environment have been extensively modelled. Processes that might affect physical processes such as erosion, sediment transport and the slamming and turbulence forces experienced in shallow waters and coastlines include scattering, reflection and diffraction of waves, and wave amplification, phase change and grouping owing to interactions with multiple structures (e.g. Maniar & Newman 1997, Evans & Porter 1999, Ohl *et al.* 2001a, 2001b, Neelamani & Rajendran 2002, Silva *et al.* 2003, Duclos & Clément 2004). It has also been pointed out by Falcão (2009) that the hydrodynamics of floating wave energy converters have similarities with the dynamics of ships on waves at sea for which there is a long history of research (e.g. Conolly 1972). Much research has been focused on the hydrodynamic properties of wave energy converter devices, particularly with regard to their performance and interactions between devices in arrays (e.g. McIver 1994, Mavrakos & McIver 1997, Agamloh *et al.* 2008, Child & Venugopal 2009, De Backer *et al.* 2010). Fewer studies, however, have examined how energy extraction may change the nature of the wave climate and the environmental implications of any changes. Falnes & Budal (1982) showed that total absorption of the incident wave is theoretically possible with multiple rows of heaving point absorbers performing optimally. In practice, of course, this type of maximal energy absorption will never be feasible, and various more recent studies have considered cases where there is some energy transmission through an array of devices. Venugopal & Smith (2007) used MIKE 21 wave suite models to examine the potential for wave climate changes to be caused by an array of wave energy devices, calibrating the models for the west coast of Orkney. Modelling results indicated downstream reductions in the range 13–69%, but also with regions of augmented wave energy due to diffraction and interference. Other modelling studies related to wave energy test locations in Cornwall, Spain and Portugal have found varying levels of influence of energy extraction on nearshore wave conditions (Millar *et al.* 2007, Vidal *et al.* 2007, Palha *et al.* 2010). Millar *et al.* (2007) applied the SWAN model (Booij *et al.* 1999) to the Wave Hub site, 20 km offshore from the north coast of Cornwall, showing that for realistic levels of wave energy transmission through a 30 MW wave farm there would be a maximum change of 4 cm in significant wave height at the shoreline, and on average 1 cm or less, and that the magnitude of change would depend on the direction from which waves approached the shoreline. These results apply to nearshore locations (10 m depth), reflecting concerns about changes in wave energy reaching the coast. Much larger changes in wave height would be expected in deeper water in the vicinity of the wave farm, but such changes are probably of lesser significance in terms of environmental and ecological consequences. It is worth noting, however, that based on modelling work by Halcrow Group Ltd, ASR (2007) considered that Millar *et al.* (2007) substantially underestimated the potential scale of impact on nearshore wave heights by a Wave Hub development. Palha *et al.* (2010) used the REFDIF model (Dalrymple & Kirby 1991) to examine wave energy absorption by wave farms off the Portuguese coast. Wave farms consisted of 270 Pelamis devices rated at 0.75 MW (total rating of 202.5 MW), and up to six wave farms were modelled within a 320 km^2 pilot zone. Changes in nearshore (10 m depth) significant wave heights were generally less than

23% (28 cm) in July and less than 9% (25 cm) in January. Alexandre *et al.* (2009) pointed out that studies in which energy extraction is modelled as frequency-independent transmission coefficients do not take account of the fact that devices are optimised for operation at particular sea-states, such that energy reduction should only occur over a particular frequency range. They used the SWAN model to investigate the effect of frequency-dependent energy extraction on the nearshore wave climate, finding that the magnitudes of reductions in energy flux consequent on extracting energy from the peak of the wave spectrum are diluted by associated reductions in energy dissipation between the extraction site and the shore, resulting in only small reductions in breaking wave height at the shore. Nevertheless, they highlight that these changes may still be important in terms of their effects on wave-erosion and longshore currents.

As noted above, in terms of environmental consequences, reductions in wave energy are most likely to be important at or near the shoreline where much of the accumulated energy of a wave field is expended in natural circumstances (e.g. Denny 1988). The environmental implications of intercepting and extracting wave energy are thus mainly contained within the littoral and shallow sublittoral. Monitoring protocols to measure biological responses to reductions in exposure to wave energy are being developed for intertidal organisms on rocky shores (Want *et al.* submitted), with plans also for application in sublittoral environments (Andrew Want and colleagues, ICIT, Heriot-Watt University). Clearly, modification of wave climate has the potential to affect patterns of coastal erosion, sediment deposition and sediment transport, as well, perhaps, as local mixing. However, there are major uncertainties about any impacts (Michel *et al.* 2007, Simas *et al.* 2009), and there is little physical evidence yet available in practice such that it is difficult to generalise across locations. As with extracting energy from tidal currents, environmental implications of extracting wave energy is probably best considered on a case by case basis with environmental impact assessment along the lines set out by EMEC (2008).

Depth-induced breaking of waves at and near the shoreline is the most important mechanism of wave energy dissipation (e.g. Lippmann *et al.* 1996), but there are other components of wave energy flux that potentially could be affected by energy extraction. As noted by Alexandre *et al.* (2009), whitecapping and, particularly, bottom friction play a role in total energy dissipation and can modify the total amount of energy that reaches littoral environments in breaking waves. Whitecapping is the spilling of waves in deep water and depends on wave steepness. This is likely to be a very minor source of energy loss and its direct effects on physical processes can perhaps be disregarded. Bottom friction may be more important. This depends on velocity at the seabed and can be more important for low frequencies in the wave spectrum. The thickness of the boundary layer caused by interaction of wave and current motions with rough bottoms plays an important role in determining sediment transport (van Rijn 1989, 2007, Sana & Tanaka 2007), and the boundary layer is likely also to define conditions experienced by benthic communities (Denny 1988). Moreover, the wave boundary layer may be important in defining wave-current interactions given the additional resistance to current flow induced by the presence of waves (Grant & Madsen 1979). This topic merits further research in relation to marine renewable energy developments since little information is available on how wave energy extraction might impact upon boundary layer processes and wave-current interactions, and on what would be the environmental consequences of any changes. Michel *et al.* (2007) cite results of modelling studies by Halcrow Group Ltd showing both increases and decreases in current velocities potentially induced by developments at the Wave Hub but do not specify the mechanism for these changes.

2.3. Sediment transport

Sediment currently present in the marine environment around Britain and Ireland is largely a product of the massive erosion of rock that took place during the last glaciation around 18 000 years ago (Morris 2010a). Mud, sand and shingle has been supplied to the marine environment during the long process of glacial retreat, during which time the sea level has risen by 100 m or more, and coasts and bed-forms have been shaped to fit energy inputs from waves and tidal currents. Mobile sediments (i.e. fine particles) tend to be transported to locations where there is insufficient energy to re-mobilise them. Supply to any given location is restricted mainly to re-mobilisation of existing sediment, with very limited input of new sediment from coastal erosion. According to Morris (2010b): 'The coast can be likened to a giant energy management system. Each part of the coast reflects the mechanisms available to absorb or reflect energy. If the energy is absorbed, then the coastline is relatively stable, while erosion means that there is insufficient buffering to absorb the energy.' This analogy can perhaps be extended to cover the entire marine environment, and given the relationship between hydrokinetic energy and sediment transport and deposition it is clear that extraction of energy from waves and tidal currents has the potential to impact upon natural sedimentary processes. It is worth noting that coastal sediment processes are currently also affected by sea level rises caused by climate change (Morris 2010a, 2010c).

Wave and tidal energy extraction can be envisaged to have two types of influence on sedimentary processes. In the first case, there may be near-field effects in terms of localised increases in scour and associated deposition of re-suspended sediment elsewhere. Much of this may be due to the physical presence of devices, and particularly seabed attachments and moorings, rather than to the extraction of energy *per se*, although, as noted in the preceding sections, this may also play a part. Michel *et al.* (2007) reviewed studies relevant to localised scour around offshore wind energy structures, and highlighted the relevance of this information also for the 'wet' marine renewables. Scour appears to be related to the presence of vortices and vortex shedding around structures. The primary influence is from currents rather than waves, although waves may also be relevant in shallow waters. The other type of influence on sedimentary process is far-field changes induced by energy extraction. Michel *et al.* (2007) highlighted the primary far-field impacts as changes in sea-bed topography, littoral zone limits and sediment transport rates, with regional implications for erosion and deposition in areas where this would not otherwise occur. Neill *et al.* (2009) modelled the effects of tidal current energy extraction on large-scale sediment dynamics. They concluded that energy extraction could affect patterns of erosion and deposition at distances of 50 km from the point of extraction (in the case of the Bristol Channel), with effects depending on the degree of asymmetry in the tidal system (which determines the net transport vector). They pointed out that energy extraction can reduce the overall magnitude of bed-level change and suggested that this could be seen as a counter-balance to increases in wave-induced bed stress expected under climate change scenarios.

In general, although it is clear that there is potential for wave and tidal current energy extraction (and associated activities) to impact upon sedimentary processes, there is rather little information on what might happen in practice. There is an urgent need for new research specifically aimed at identifying the ways in which wave and tidal energy developments might impact upon sediment dynamics and coastal processes in general (Amoudry *et al.* 2009). An improved understanding of potential far-field effects is particularly important. Site-specific studies would be particularly valuable, with sediment dynamics incorporated as transport processes within large-scale hydrodynamic models such as SUNTANS.

3. Ecological processes

Wave and tidal energy developments could interact with ecological processes in two obvious ways. Firstly, as highlighted above, extraction of energy and device operation have potential implications for physical processes in both the near- and far-fields of developments, with consequences for ecological processes that depend on these for their functioning. Secondly, developments and the activities necessary to construct, connect, maintain and decommission them may directly impact upon species and habitats, e.g. by smothering or directly damaging seabed habitats.

3.1. Hydrodynamics and sediment dynamics

In considering interactions between wave and tidal developments and physical processes (see above), a number of possible interventions in ecological processes were noted. Many ecological factors determining the occurrence of marine species can be defined in terms of hydrodynamics, such that there is clearly scope for energy extraction to have ecological effects (see Shields *et al.* 2011 for a review). Sediment type is another important habitat determinant, from which it follows that anything that can affect sediment mobility and distribution also has ecological implications. For example, seagrass beds have been shown to be highly vulnerable to the deposition of sand (Craig *et al.* 2008).

One of the most important ways in which effects on physical processes would have implications for ecological processes is in determining trophic linkages within marine ecosystems. As already noted above, Scott (2007) and Scott *et al.* (2007) emphasise the role of water column processes in trophic coupling in shallow water environments, with particular importance in determining foraging habitat for top predators (seabirds and mammals). As we have seen, energy extraction has the potential to affect vertical mixing structure and the location of fronts at both near- and far-fields. Sharples (2008) showed that primary productivity is strongly related to tidal mixing processes, from which it follows that intervention in hydrodynamics by tidal energy extraction has the potential to influence (both positively and negatively?) marine productivity at a very basic level. Much research is needed to clarify the potential for impacts here, but in ecological terms this is probably the most important way in which marine renewable energy developments could affect marine environments.

Transport of larvae and other propagules of marine organisms is another crucial linkage in marine ecosystems that could potentially be impacted by intervention in hydrodynamic processes. Timing and location of release of larvae, for example, is often finely tuned to provide favourable feeding conditions and transport to favourable settling grounds. Disruption of any of these factors has potential implications that extend far beyond the organisms affected, particularly through trophic linkages. Research in this area is lacking in relation to marine renewable energy, a gap which should urgently be addressed alongside physical modelling at a systemic level.

It is worth noting that an 'early warning' facility for detecting ecological changes is another urgent research priority, the more so because it is relevant to setting baselines *prior* to developments. Shields *et al.* (2011) advocate the use of sentinel species that are sensitive to changes in hydrodynamic conditions. Such species may not necessarily be of conservation concern in their own right, but can provide indications of more systemic changes which may be of concern. Want *et al.* (submitted) provide examples of monitoring strategies for rocky shores based on sentinel species that may respond to commercial extraction of wave energy, and put particular emphasis on detecting responses against a background of concurrent climate change.

3.2. Direct habitat impacts

Wave and tidal energy developments are likely to be extremely variable in the details of their design and operation, and all these aspects will have a bearing on the level and nature of potential impacts (a Scottish Government-funded study coordinated by Aquatera Ltd will shortly report on potential impacts from different design elements). However, all installations will require some contact with the seabed, in the form of either moorings or the device itself, as well as electrical cables or pipes connecting devices to the shore. These structures may be substantial, and it is inevitable that seabed habitats will be damaged or modified by their presence. In many cases this type of direct impact may not be of little or no concern in terms of marine conservation, particularly in the case of tidal developments over areas of exposed bedrock, but the presence of high conservation value biogenic reef structures such as horse mussel (*Modiolus modiolus*) beds may be a relevant factor in determining areas suitable for development. Any effect on seabed habitats is likely to have wider implications for benthic communities and for interspecific interactions (e.g. Nelson *et al.* 2008).

It is worth noting that possible impacts on seabed environments are not confined to one-off effects of habitat occupancy by development structures. Particularly where there are moving, or at least moveable, elements, chronic cumulative impacts may be possible. 'Strumming' of cables, for example, may incise into rocky outcrops, although impacts on seabed communities may be minor (Kogan *et al.*, 2006). The scope for habitat impacts also differs between different stages of development. Construction activities, in particular, may present particular environmental challenges, e.g. from pile-driving, that are not relevant to the operation, maintenance and decommissioning of developments.

Habitat loss may also occur through disturbance rather than damage. Inger *et al.* (2009) cite the example of foraging habitat for sea ducks, which may be displaced from development areas. This issue has been explored in relation to offshore wind farms (e.g. Kaiser *et al.* 2002, Larsen & Guillemette 2007), but is undoubtedly also relevant to wave and tidal developments. Data on marine habitats and other aspects of the marine environment are extensively considered within emerging guidelines for locating marine energy developments (e.g. Marine Scotland 2010). At present, one of the main factors limiting our appreciation of the potential for marine renewable energy developments to impact upon marine species and habitats is our understanding of the relationships between community types, species distributions, spawning areas, etc., and exploitable energy resources. Such relationships could be causal, as in energy-related factors defining the ecological niches of species, or simply a matter of spatial overlaps based on unrelated factors. Either way, overlap in spatial domains are crucial in determining the potential for interactions or impacts. Spatial information exists for both energy resources (DTI 2004) and for many aspects of the marine environment, including marine habitat types (e.g. EUSeaMap, 2011, based on the EUNIS classification), seabirds (e.g. Söhle *et al.* 2006), cetaceans (e.g. Reid *et al.* 2003), fish and marine invertebrates (e.g. DATRAS 2011) and various other biological and oceanographic aspects of marine environments (e.g. ICES 2011). In some cases there have been syntheses of such data to map sensitivities in relation to human activities, e.g. the sensitivity of commercial fish species to seismic and other activities by the UK oil and gas industry (Coull *et al.* 1998). These, and many other data sources, provide the basis for future exploration of the potential for wave and tidal energy developments to impact upon marine ecosystems, potentially including the development of predictive modelling capacity to examine future scenarios. This is a major priority for the future to underpin Environmental Impact Assessment requirements in relation to proposed developments.

4. Noise impacts

One of the emergent environmental concerns in recent years has been the levels of noise in the marine environment arising as a consequence of man's activities. There are many measures of sound pressure levels, but the rms (root mean squared) which provides an averaged value for continuous sounds (in dB re 1μPa – decibels relative to one micropascal) is frequently preferred. For impulsive sounds measures of impulse or peak-to-peak values are used as the impact on sensitive marine organisms is from the short duration, high intensity variation in the signal rather than from exposure to a continuous sound source. These measures which better characterise short lived high energy pulses would be applied, for example, to pile driving, use of explosives, and seismic sound sources such as air guns. In air dB(A) re 20μPa is more routinely used as it is a measure adjusted for the frequency-specific threshold of human hearing.

For marine renewables the highest sound pressure levels recorded are those associated with the pile driving for offshore wind installations. This repeated hammering activity generates very high energy pulses, whereas wave and tidal devices have thus far avoided the use of pile driving, and on hard seabeds have used the technique of pile drilling for seabed fixture. Table 1 provides a summary of sound pressure levels from pile drilling and from various vessels and operations used during the installation of wave and tidal devices.

Table 1. Source levels from anthropogenic underwater noise for various activities.

Activity/Source	**Reported levels / Estimate**	**Reference**
Pile driving (4.0-4.7m diameter piles)	243-257 dB re 1μPa at 1m (peak to peak)	Nedwell *et al.* (2007)
Pile driving (1.8m diameter piles)	226 - 250 dB re 1μPa at 1m (peak to peak)	Bailey *et al.* (2010)
Pile driving (2.4m diameter piles)	185-196 dB re 1μPa at 100m (rms) 197-207 dB re1μPa at 100m (peak to peak)	Caltrans (2001)
DP Drillships	190 dB re 1μPa at 1m (rms)	NRC (2003)
Larger vessels	180-190 dB re 1μPa at 1m (rms)	OSPAR Commission (2009)
Pile Drilling	160-180 dB re 1μPa at 1m (rms)	ICIT, Nedwell & Brooker (2008)
Small work-boats (with thrusters) and ships	160-180 dB re 1μPa at 1m (rms)	OSPAR Commission (2009) and ICIT
Wave and tidal devices	165-175 dB re 1μPa at 1m (rms)	OSPAR Commission (2009) – probably includes pile drilling for installation and

	<160 dB re 1µPa at 1m (rms) during device operations	also vessel activity. ICIT estimate excluding installation and vessel activity

In general the description of sound transmission loss from a sound source underwater (and in air), and the corresponding zone of effect for a vulnerable target species requires:

1) the determination of the sound pressure level of the sound source (usually for continuous sounds in rms dB re 1µPa at 1 m in water, and rms dB(A) re 20 µPa at 1 m in air);

2) the determination of background levels in the area occupied by the target species;

3) the setting of appropriate thresholds of concern for the target species;

4) a model of underwater sound attenuation, which describes transmission loss appropriately for the area under consideration;

5) the determination of the zone within which such thresholds are exceeded or the distance required before background noise levels are likely to mask any signal from the sound source.

Generally models of sound propagation take the form:

$$TL = N\log_{10}(r) + Ar$$

Where the Transmission Loss (*TL*) at distance (*r*) is expressed in terms of a spreading loss factor (*N*) and absorption coefficient (*A*), though the latter is not always used. In theory in the open sea in deeper water spherical spreading occurs and $N = 20$; in shallower coastal water and channels cylindrical spreading can be modelled using $N = 10$. In practice in shallower water studies, empirically derived models have a range of values of *N* often of an intermediate form with $N = 15$. For example during the installation of the SeaGen tidal turbine in Strangford Lough measurements were made of the sound pressure levels generated by the pile drilling, and the results of these compared with a simple model of sound attenuation, in this case $TL = 16\log_{10}(r)$ are shown in Figure 1.

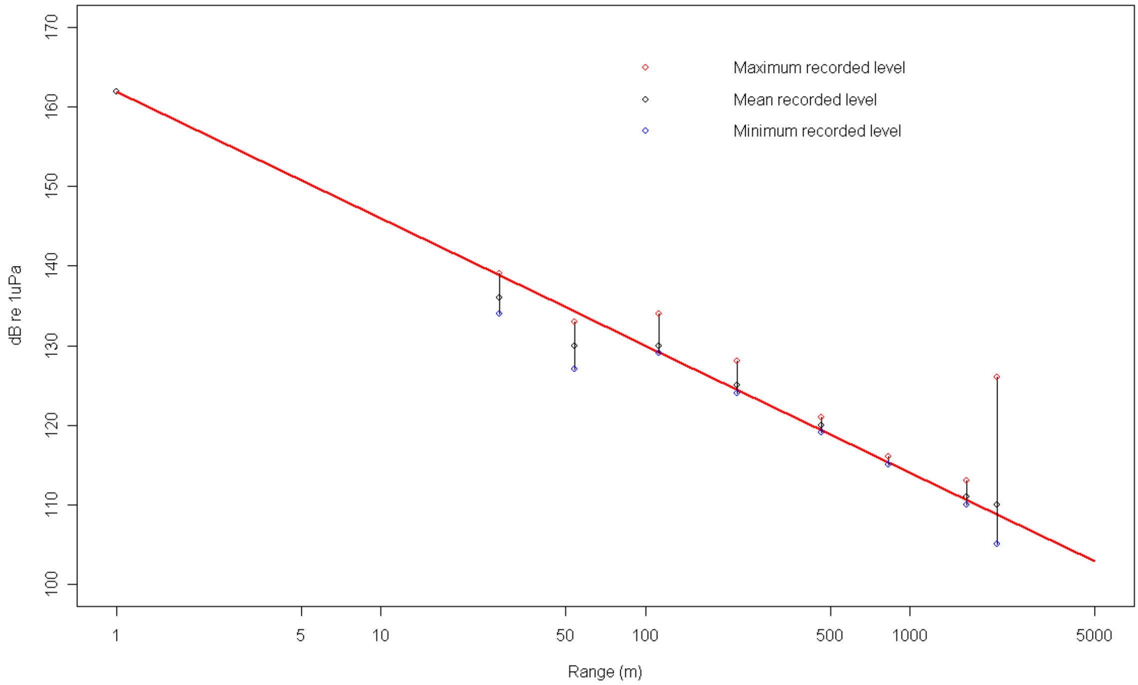

Figure 1. Fit of field data ranges to empirically derived model of sound attenuation from pile drilling for the SeaGen tidal turbine in Strangford Lough.

(Source: Nedwell & Brooker, 2008)

In addition to the level of background noise there are a number of thresholds that have gained acceptance in the scientific literature when considering the effects of underwater noise on vulnerable species:

1) Auditory injury or permanent threshold shift in hearing (PTS);
2) Temporary threshold shift in hearing (TTS);
3) Behavioural disturbance thresholds (BHT) – sometimes ranked as minor or major;
4) Hearing Threshold (sometimes "ht") or auditory threshold for the species concerned.

Generally the latter, auditory thresholds, are used to analyse measured data to determine *perceived* noise levels for the species concerned. This mirrors the approach employed with human perception of noise levels.

Bailey *et al.* (2010) conclude that for pinnipeds PTS onset would occur within a 20 m zone of the pile driving operation for the Beatrice Wind Farm in the Moray Firth and TTS onset within a 40 m zone. They estimated the source levels ranging from 226–250 dB re 1μPa at 1 m from measurements taken at close range to the piling operation and from all measurements over a much wider area respectively. They note that behavioural disturbance may have occurred up to 50 km for bottlenose dolphins (*Tursiops truncatus*). As well as behavioural disturbance which may take the form of avoidance, there is also concern expressed in the literature from increases in general anthropogenic noise which may mask cetacean communications and also alter their vocalisation. Rendell & Gordon (1999) noted that long-finned pilot whales (*Globi-*

cephala melaena) altered the type of vocalisation in the presence of military sonar signals.

Historically the behavioural disturbance threshold proposed by the US National Marine Fisheries Service (NMFS) for the lower limit of auditory damage (180dB re 1µPa) has been used.

Harris *et al.* (2001) suggested Minor Disturbance and Major Disturbance thresholds of 160 and 200 dB re 1µPa (peak to peak, not rms) for pinnipeds, and more recent work by Southall *et al.* (2007) suggests Minor Disturbance and Major Disturbance thresholds of 90 and 155 dB re 1µPa (peak to peak) for the harbour porpoise (*Phocoena phocoena*). Again it is important to remember that these threshold values are for high-energy, short bursts from pile driving, underwater explosives and seismic sound sources. Pile driving has not been used to date in the installation of wave and tidal devices with pile drilling and anchor blocks being used instead for fixtures on hard seabeds, and a variety of anchors on softer sediments. In general it is unlikely that sound levels from the normal operation of wave and tidal devices will exceed those of vessels and other activities used during installation and maintenance, simply the greater the noise levels from such devices the lower their efficiency will be.

The OSPAR Commission (2009) provides a general review of impacts of underwater anthropogenic noise; for a review of international safety standards in this respect, see Compton *et al.* (2007). Although some expensive mitigative measures have been investigated (such as the use of bubble curtains) the general approach adopted has been to require a marine mammal observer (MMO) on board a suitable attendant vessel during such operations. If marine mammals are present in the vicinity, the start of operations is delayed, and usually, where practicable (i.e. pile driving and pile drilling) a soft start, then gradual ramping up, to the operations is required.

Particular emphasis has been placed on studies of underwater noise in relation to sensitive sites for cetaceans such as the Moray Firth Special Area of Conservation, and also the Fall of Warness, the EMEC tidal device test site, where seal haul-outs during seal pupping may be particularly sensitive to disturbance from underwater sound.

5. Collisions with mobile fauna

Both offshore and onshore wind projects have had to address concerns over collisions with birds and the rotors of the turbine, and in the marine environment potential collisions with the rotors of tidal turbines and the plankton and nekton are clearly possible. Most at risk are the larger plankton floating in the water column (e.g. jellyfishes), but it has been hypothesised that fatal injury to fishes may occur (e.g. van Haren 2010) and certainly fatalities to seals have been recorded from the animals being drawn through ducted propellers on vessels (Thomson *et al.* 2010). Most concerns have focussed on seal and cetaceans and few on diving seabirds.

For the SeaGen tidal turbine development in Strangford Lough the developers were required to have a MMO on watch during all periods of generation for the first 6 months. If seals were sighted up-stream of the device then it was stopped and generation halted. After this initial period the MMO was replaced by a forward-looking sonar which has resulted in the device shut-down on numerous occasions (Graham Savage, pers. comm.).

Some studies have attempted to model the impact on marine mammals and fishes from interactions with the rotors. Wilson *et al.* (2007) modelled interactions with 100 horizontal axis (8 m radius) turbines operating off the Scottish coast and existing populations of herring (*Clupea harengus*) and harbour porpoises. The model predicted that in a year of operation, 2% of the herring population and 3.6–10.7% of the porpoise population would encounter a rotating blade, but the authors stress that this ignores any avoidance or evasive action on the part of the animals, and thus by no means should be taken to suggest that such a proportion of the population would be fatally injured.

Neither the MMO monitoring for the SeaGen device, nor modelling studies provide indications of the actual risk to organisms in the nekton. In response to this at least one tidal developer is installing collision detection equipment on its tidal turbine. Scotrenewables are deploying collision detection hydrophones and cameras on the SRT250 prototype device which is to be deployed at EMEC in the next few months. The hydrophone signal is processed and this data used to detect collisions with the rotors, and thereafter the video files for corresponding times will be examined (Scotrenewables 2010). A further Joint Industry Project is being developed with Scotrenewables to automate processing of the video files in an attempt to determine whether near misses as well as collisions can be detected. Such data on collision and near misses would enable ground-truthing of collision models.

6. Provision of new ecological space

Man-made structures on the seabed are often considered to be of high potential value in terms of providing new living space for marine organisms, with potential benefits for marine biodiversity, productivity and fisheries, and this may well be true of marine renewable energy developments (Inger *et al.* 2009, Langhamer & Wilhelmsson 2009, Langhamer *et al.* 2009, Langhamer *et al.* 2010). Creation of new habitat by the introduction of artificial structures into marine environments has been shown to increase the local abundance and biomass of fish compared with surrounding natural habitats (e.g. Bohnsack *et al.* 1994). Abundance and diversity of other marine organisms may also be enhanced, although it is worth noting that benthic organisms may be heavily impacted by predation from fish attracted to artificial structures (Davis *et al.* 1982, Langlois *et al.* 2005).

As noted by Inger *et al.* (2009), another way that marine renewable energy developments may provide new ecological space is by acting as fish aggregation devices (FADs). This may be particularly true where devices have floating components. For reasons that are as yet unclear, fish often aggregate around floating objects (e.g. Castro *et al.* 2002). Fishermen may take advantage of increases in local density, but the population-level consequences of this behaviour are not clear. Inger *et al.* (2009) highlight that FADs may increase fishing mortality whilst contributing nothing towards increased recruitment levels.

7. Displacement of other human activities – fishing

Fishing is here singled out as a human activity that should be considered alongside environmental interactions of wave and tidal energy developments because it is fundamentally a trophic process, as dependent on the 'normal' functioning of marine ecosystems as any top predator such as a seabird or marine mammal. Furthermore, there is great potential for spatial interactions, given that exclusion of fishing from traditional grounds provides further ecological feedback from the response of target species.

While it is hard to see how small-scale deployments of wave and tide (and offshore wind) developments will have a major effect on fisheries, as the scale of offshore farms increases so do the potential impacts on fish stocks and fisheries. As with other aspects of marine ecosystems, this has to be considered against the distribution shifts in marine fish stocks already being observed as a consequence of climate change (e.g. Perry *et al.* 2005). As with other components of marine ecosystems, fish populations have the potential to be affected by changes in sedimentation patterns, turbidity and water flow and by any associated changes in the benthos. These factors may affect fish populations at different life-history stages, with subtle effects on spawning, feeding and migration.

Bell *et al.* (2010) compared the distribution of UK fishery landings with wave and tidal energy resources and concluded that the potential for overlap between fisheries and energy extraction is probably small at a national scale, but of great potential importance at more local scales. The most important interactions appear likely to occur close inshore, and given the concentration of the wave and, particularly, the tidal energy resource at a few localities, notably the Northern and Western Isles of Scotland, there is potential for any interactions to be very important at regional or local scales. A lack of detailed catch and effort data at a fine spatial scale currently hampers our ability to examine the real potential for interaction at these scales given current development plans. Bell *et al.* (2010) also concluded that any spatial interactions are likely to be most important for species that are sedentary or of limited mobility at the spatial scale of developments. This is because potential spatial overlaps are greatest for stocks that exist over small spatial scales and also because effects depend upon the ability to move between development areas and unaffected areas. Shellfish, particularly crustaceans such as lobsters, have possibly the greatest potential in this respect, and it is worth noting that inshore lobster habitats are likely to overlap strongly with areas of interest to wave energy developers. There is scope for deliberate enhancement of habitat around marine renewable energy developments, e.g. to provide substrates suitable for juvenile lobsters, and even for stock enhancement through release of hatchery-reared individuals into suitable areas. This is a focus for current research at the EMEC wave test site at Billia Croo in Orkney.

Whether by regulation and the establishment of explicit no-take zones around offshore energy farms, or just by avoidance, such areas are likely to become effective no-take zones, with fishermen experiencing a loss of access, and the (shell)fish populations within these areas experiencing some protection from fishing. As noted by Bell *et al.* (2010), exclusion zones around marine renewable energy developments have scope to influence both fishery yield and the spawning potential of target stocks, with potential benefits for the sustainability of fishing (see also Side & Jowitt 2005). Much has also been written about the potential for such fishery exclusion zones to act as *de facto* Marine Protected Areas (MPAs) (e.g. Inger *et al.* 2009).

As noted above, fish may be beneficiaries of the new ecological space provided by devices and device arrays, which may function both as artificial reefs and as FADs. The creation of new artificial niches for fish may result in an increased density of fish being inaccessible to fisheries. However, as pointed out by Inger *et al.* (2009), FADs act to concentrate fish stocks rather than to increase recruitment, thus providing a potential for overexploitation that runs counter to any MPA effects.

Tidal turbines have the capacity to impact directly on fish populations by additional mortality from fish colliding with moving rotor blades. As an approximation, the volume swept by a tidal turbine rotor is of a similar magnitude to that of a moderately sized trawler. While likely to be a substantial overestimate, some alarming reports (van Haren 2010) suggest major fish mortalities as a consequence. In practice, most fish species likely to occur in the domain of tidal turbine rotors may well be sufficiently mobile, manoeuvrable and alert to avoid collisions. Additional mortality could also arise from the changed hydrodynamic conditions around tidal devices, with turbulent flows over the rotors forcing small fishes to the surface. As noted above, natural turbulent upwellings of this kind are exploited by feeding seabirds, and thus one might see this as a positive impact for some components of marine ecosystems.

Various other issues relating to marine renewable energy developments may be relevant to fish and hence fisheries, including noise (see above) and electromagnetic fields (EMF). Much research has been devoted to the latter, in relation to EMF from wind farm cables (e.g. Walker 2001, Gill *et al.* 2005). Electrical and magnetic senses exist in both bony fish and elasmobranchs (among other marine vertebrates), and it is certainly possible for EMF effects to disrupt in orientation, migration and prey detection behaviours. Knowledge of essential fish habitats and migration routes should certainly be taken into account in spatial planning decisions concerning routing of electrical cables from marine renewable energy developments, but the population level consequences of EMF disruption are as yet unclear (e.g. Öhman *et al.* 2007). Possibly the most important potential impacts on fish populations are likely to stem from disruption of ecosystem processes at a system level, stemming from far-field changes in hydrodynamics and sediment transport (see above). This further highlights the urgent need for research into whole system responses to upscaling of marine renewable energy developments.

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