COMMISSION OF THE
EUROPEAN COMMUNITIES

COOPERATION

Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Grant agreement number: 213380

EquiMar

Deliverable D1.1

Global analysis of pre-normative research activities for marine energy

Grant Agreement number: 213380

Project acronym: EQUIMAR

Project title: Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Deliverable D1.1

Global analysis of pre-normative research activities for marine energy

Pierpaolo Ricci, José Luis Villate, Mattia Scuotto, Laura Zubiate
Robotiker-Tecnalia
Tom Davey
University of Edinburgh
George H. Smith, Helen Smith
University of Exeter
Cristina Huertas-Olivares, Frank Neumann
Wave Energy Centre
Tim Stallard
University of Manchester
Claudio Bittencourt Ferreira, Jonathan Flinn, Thomas Boehme
Det Norske Veritas
Andrew Grant, Cameron Johnstone
University of Strathclyde
Chris Retzler
Pelamis Wave Power
Hans Christian Sorensen
Wave Dragon

February 2009

Summary

The present report addresses the current state of marine energy technology by compiling, comparing and analysing existing guidelines, recommendations, protocols and other technical specifications for assessment, modelling, design and analysis of marine energy technologies.

It is intended to provide an extensive collection of fundamental references for wave and tidal energy research and a first input basis for future work within the EquiMar Consortium. Background information is based on the outcomes from previous National, European and International RTD projects and particular attention has been devoted to general and globally aimed approaches rather than methodologies defined for a specific kind of device. The idea is to analyse previous established results in the marine energy pre-normative field and identify possible data and knowledge gaps to be faced in the future for improvement and harmonisation of the assessment techniques of marine energy devices.

This deliverable is subdivided in 7 chapters: The first one represents an introduction to the current status of marine energy and a general presentation of previous international research programs based on the collaboration between academic and industrial partners from different countries.

Chapters from 2 to 6 summarise background information available in different specific technical subjects and are connected to the Work Packages included in the EquiMar project. The five areas covered are:

- Physical Environment and Resource Specification
- Concept Appraisal, Device Modelling and Performance Assessment
- Sea Trial Testing and Full-Scale Design and Deployment
- Policy Issues and Environmental Impact Requirements
- Economic Assessment of Large-Scale Deployment

Each of these sections includes tables and a list of references for deeper knowledge. Even if most of the documents described represent fundamental outcomes generally acknowledged by the partners of the Consortium it has to be said that, for reasons of space, such list cannot be exhaustive and that more detailed insight of specific issues will be addressed as part of the future work of the EquiMar project.

Chapter 7 resumes the content of the report and addresses conclusions and recommendations derived by the analysis of the information collected.

Due to the early stage of development of marine energy technologies and given the current contemporary effort by several research entities towards the large-scale industrialisation and commercialisation of this sector, the information contained in this report is subject to rapid modification and reviews and updates might be provided in the future in conjunction with partners and outside stakeholders.

CONTENTS

1. INTRODUCTION

1.1 THE CURRENT STATUS OF MARINE ENERGY

The interest in renewable energy technologies has been growing exponentially in recent years. The increase of energy demand, the contemporary variation of the price of oil and concerns about global warming have concurred to favour the development of renewable energies, among which wind energy has achieved a remarkable evolution.

Marine energy has also enjoyed this consistent support and has recently made important progress towards commercially viable technologies. Nowadays various device concepts exist and several of these have already come to a pre-commercial stage.

Oceans constitute more than two-thirds of the earth’s surface and act as a large collector of solar energy. This concentrated energy is transferred through complex wind-wave interactions into wave motion. In addition, tidal variations are created due to earth-moon gravitational pulls, rotational tilt and rate of spinning. Global hydrological cycles, climatic conditions and geographic features contribute to other forms of energy flux.

Marine renewable energy resources can be broadly categorized into: Waves, Tidal level changes, Tidal currents, temperature gradients and salinity gradients.

New technologies in each of these fields are being developed at a national and international level around the world. Wave and tidal stream energy particularly have been investigated for decades and research in these subjects has come to consistent results, both theoretically and experimentally and the most advanced technologies currently being deployed and tested belong to these categories. Also, the majority of the commercial projects and private investments are concentrating in wave and tidal current devices.

This report is entirely based, therefore, on these types of devices. However, considering the variety and diversity of the different concepts, it is likely that much of the information collected will be useful for other marine energy applications.

The number of developers and private or public entities involved in this field is continuously growing and a list of all the ongoing projects and devices being developed at the moment would be long and necessarily incomplete. A global overview of the current research and deployment marine energy activities in 24 countries can be found in the 2007 annual report issued by the International Energy Agency – Implementing Agreement on Ocean Energy Systems ([1]).

Regarding wave energy device developers, a recent updated state-of-the-art report ([2]) has been produced by the University College of Cork within the European project WAVEPLAM (see section 1.3). This document includes a review of existing wave technologies based on a preliminary classification and a description of their own state of development.

A similarly extensive description of existing tidal renewable energy technologies available at the present date is included in the Annex 3 of the Tidal Energy Roadmap ([3]) produced within the Co-ordinated Action on Ocean Energy (see section 1.2).

1.2 AN OUTLINE OF THE PREVIOUS PRE-NORMATIVE RESEARCH ACTIVITIES

The contemporary development of marine energy technologies in several countries and the technological challenges posed by their design and deployment has generated discussion and controversy among the stakeholders on the different solutions proposed to overcome these problems.

The existence of a large number of very different projects and concepts in a sector that is not yet fully commercialised has also imposed the necessity of a mechanism for inter-comparison between them. Advances on an industrial basis will be promoted through a careful comparison of the differences in the concepts, but perhaps more importantly through the identification of common themes and methodologies. This need for a global equitable evaluation of marine energy converters is particularly important to define common baselines and recommendations for development, testing and measurement that could favour the emergence of a new global market.

To this aim, a significant research effort has recently been devoted to the definition of a number of protocols and standards, trying to organise and compile the previous experiences in the field in a series of recommendations and guidelines regarding project development, performance and site assessment, engineering and safety requirements and global evaluation. Much of the documentation resulting from these activities will be presented and described in the following sections. A general summary of these various approaches can be found in Table 1.

Table 1 General resume of the previous global pre-normative research activities

Project (organisation)	**Year**	**Scope**	**Status**
WaveNet (various institutions)	2003	Not aimed to provide proper guidelines but more focusing on collecting technical efforts and conclusions on marine energy systems through interaction between European institutions	Completed in 2003. Even if partially outdated it still represents one of the best technical summaries on ocean energy with a lot of useful information
Marine Energy Challenge (The Carbon Trust)	2006	Addresses a comparison methodology for marine energy devices based on the estimation of the cost of energy	A study has been completed in 2006. The method proposed is easily applicable and still quite used by stakeholders as preliminary indicator
MRDF (DTI)	2006	Support of wave and tidal demonstration project and related research	Applications for funds are open. The performance protocols are completed.
Ireland National Strategy for Ocean Energy (SEI-HRMC)	2006	A number of safety and operational criteria and mandatory independent structural sea worthiness evaluation process for access to 1:4 scale open sea test site in Galway Bay. Plus scaling protocol for wave energy devices in four phases (UCC-HMRC)	Concluded, but relatively site-specific and developed ‘in-house’ by one single institution/country
EPRI	2004	Feasibility report of wave power for a range of devices, considering a series of reports concerning wave and tidal resource assessment and methodologies for power estimation, performance assessment and cost accounting.	Concluded, but purpose was rather feasibility assessment. However, interesting procedures included
EMEC	2005	Definition of standards and guidelines for wave and tidal energy	Ongoing. It is contributing to standard definition for the IEC and draft guidelines on several issues can be found at the website
Marine Energy Challenge (The Carbon Trust)	2005	Guidelines for the design and operation of wave energy converters	Document with very good references to existing standards has been complete
DNV OSS-312	2008	Certification of Tidal and Wave Energy Converters	The Service Specification document was issued in Oct 2008
CA-OE (various institutions and developers)	2004-2007	To develop a common knowledge base and bring a co-ordinated approach to ocean energy research and development	Concluded. The whole project included organisation of thematic interactive workshops for discussion and knowledge sharing. A Tidal Energy Roadmap, including an up-to-date review of tidal technologies, has also been defined
UKERC (various UK institutions)	2005	To promote cohesion and coordination within the overall UK energy research effort	Ongoing. A marine energy technology roadmap has been already produced but is supposed to be updated every year through consultation
SUPERGEN phase 1 (various UK institutions)	2003-2007	Research program structured in several Work Packages to increase knowledge and understanding of marine energy	First phase is concluded. The full report includes an outline of all the results achieved and a list of all related publications. Second phase is ongoing (see below)

A short explanation of the aforementioned projects is given below:

-The WaveNet was set up as a European Commission Thematic Network to share understanding and information on the development of ocean energy systems. The outcome of this activity was a report ([4]), issued in 2003, that summarised many of the outputs of the network and that was intended to serve as a useful reference point for those interested in the status and development of the technology, the challenges faced and the potential for the industry. Eighteen organisations from nine countries took part in the network. Even if outdated, this document is still a comprehensive resume of most of the technical issues involved.

-In January 2006 the UK Department of Trade and Industry (DTI) proposed a £50 milion “Marine Renewables Deployment Fund” to support the continued development of the marine renewables sector, as part of the UK Wave and Tidal Demonstration Scheme. This scheme was designed to support the deployment of small arrays of devices with capital and revenue funds. As a requirement for the award of the funds, the developer is contracted to follow a “Wave and Tidal Energy Device Performance Protocol” and apply methodologies and recommendations concerning the measurement of the resource and performance assessment of the devices ([5]).

-In 2006 the Irish Government launched an Ocean Energy Strategy ([6]). As part of this activity Sustainable Energy Ireland (SEI) and the Marine Institute established a 1:4 scale open sea test site in Galway Bay. Access to this test site is subject to compliance with a number of safety and operational criteria. All device designs, including mooring and installation procedures are subject to a mandatory independent structural sea worthiness evaluation process before site access is offered. Within this frame the University College of Cork has proposed a scaling protocol for wave energy devices that schematises the development of a wave energy technology in four phases, each one with a defined scale and specific aims ([7]).

-In 2004 EPRI (Electric Power Research Institute) published a report, which attempted to assess the feasibility of wave power "to provide efficient, reliable, cost-effective and environmentally friendly energy supply". They describe a means whereby a range of devices could be assessed to be ready for full-scale testing or requiring further R&D to be resolved. A series of reports have been also produced concerning wave and tidal resource assessment and methodologies for power estimation, performance assessment and cost accounting ([8]).

-Since 2003 the European Marine Energy Centre (EMEC) has been publishing and disseminating several draft protocol with recommendations and standards on several issues both in wave and tidal energy. Particularly detailed is the work on resource and performance assessment but a lot of material has also been collected about design, manufacturing, grid connection, safety requirements and environmental impact assessment ([9]).

-In 2002 Det Norske Veritas (DNV) started work on the *Guidelines for the Design and Operation of Wave Energy Converters* ([10]), under the Carbon Trust Marine Energy Challenge. The guidelines are based on those developed for other areas of marine operation, with similar challenges, but with some adaptation to meet the specific needs of the marine renewable sector. A certification framework, OSS-312, identifies the requirements and process of certification. OSS-312 is focused both on safety aspects and functional requirements. The final document has been issued in October 2008.

-In Denmark a four-stage evaluation process for ocean energy devices requiring independent scrutiny at each stage has been developed. Proof of concept tests must be performed in an independent laboratory; power output must be estimated at laboratory scale against specific "standard" sea conditions before the deployment of a prototype device. At each stage results are required to be reported in a standardised way ([11]).

-The European Union's Sixth Framework Programme Co-ordinated Action on Ocean Energy (CA-OE) operated from 2004 – 2008 it investigated the RD&D needs of ocean energy technologies in a structured fashion. The CA-OE brought together the majority of the industrialists and academics involved in the research and development of the ocean energy sector and through a programme of workshops identified current practice adopted for the development of wave and tidal energy and identified the barriers and research challenges requiring to be addressed in order to bring wave and tidal energy technologies to the market. From the stakeholder engagement undertaken, it also delivered the European RD&D Tidal Energy Roadmap ([3])

-In January 2005 the UK Energy Research Centre was established to coordinate energy research in the UK. Within the Future Sources of Energy Theme a road-mapping plan for marine energy has been carried out: Reviews of existing international Marine Energy Technology Roadmaps have been carried out, and an original UK Technology Roadmap for Marine Energy is being prepared ([12] and [13]).

-The Sustainable Power Generation and Supply Initiative (SUPERGEN) is a large, collaborative programme of research based on the assembly of research "consortia" which has been tackling the large challenges of sustainable power generation and supply. ([14]) The Engineering and Physical Sciences Research Council (EPSRC) has earmarked £25M of funding over a five-year programme. Under this umbrella, the SUPERGEN: Marine program has been awarded £2.6 million to conduct research into marine energy conversion and delivery. The work is collaborative with The Robert Gordon University, Edinburgh University, Heriot-Watt University, Lancaster University and Strathclyde University. Twenty national and international marine energy and electricity supply companies have also agreed to collaborate in the research. Work completed in SuperGen Phase 1 has enhanced understanding of the extent and nature of the marine resources, how extraction of energy modifies that resource and its environment, and has pointed to how technology could be developed to enhance the effective exploitation of energy. During the lifetime of Phase 1, a selection of developers has moved from concept to prototype development and this has identified specific needs for further fundamental research. UKERC and SuperGen Marine Phase 1 organised numerous national and international meetings of the stakeholder community to agree an R&D roadmap, and to develop Protocols on behalf of the DTI for open sea testing and performance evaluation.

A key point to understand is that all of these approaches have been developed in response to specific needs and cover limited areas of the evaluation and deployment of devices. Jointly with several other contributions from other research activities, these documents provide, however, an important background and framework for future research on standard procedures and methodologies.

The present document tries to structure and analyse this information and identify key concepts and criteria for different areas in marine energy. This work represents a global resume of these different previous contributions. The objective of this analysis is the identification of the current gaps in knowledge and future technology direction and requirements. The involvement of EquiMar partners and external stakeholders will be crucial within this scope.

An investigation on the current state of the knowledge of the marine renewable sector and the most important technological challenges to be addressed has been carried out within the UKERC roadmap definition ([15]) through a series of interviews to experienced researchers in marine renewables working in four different UK institutions. This study has identified the lack of physical validation data and understanding of the wave and tidal resource as the most recognized existing gaps in knowledge. A majority of the responses has also showed agreement on offshore devices development and power take-off design as two important areas on which further research should concentrate to make a step change forward.

1.3 ONGOING INTERNATIONAL RESEARCH PROJECTS

Research in marine energy is being carried out in several institutions in Europe and in the world. Although many projects are based on specific concepts and technologies, some effort has been recently dedicated to the constitution of international consortia for the development of contents with a larger shared recognition.

Table 2 General resume of the ongoing international research projects

Project (organisation)	Year	Scope	Status
IEC TC 114 (various institutions)	2007	Development of international standards for wave and tidal technologies	Ongoing. The activities are being focused on the involvement of the partners in the process
WAVEPLAM (various EU institutions)	2008	Establishment of methods for analysis of non-technological barriers to marine energy development	Ongoing
CORES (various EU institutions)	2008	Development of new concepts and components for wave energy convertors	Ongoing
SUPERGEN phase 2 (various UK institutions)	2006	To increase knowledge and understanding of device-sea interactions of energy converters from model-scale in the laboratory to full size in the open sea	Ongoing
PRIMaRE (Un.Exeter, Un. Plymouth, SWRDA)	2004	To be a world leading institute that provides integrated multi-disciplinary expertise in Marine Energy Research, Development and Innovation	Ongoing. The activities are directly linked to Wave Hub, a new wave farm being established ten miles off the North Cornwall coast

Several research centres and private companies are involved at the same time in many of these projects facilitating the establishment of a community of stakeholders that share similar needs and often demand solution for similar problems. EquiMar is a project that was conceived within this frame but some other current research activities involving EquiMar partners deserve to be mentioned:

-The International Electrotechnical Commission (IEC) is the world's leading organization that prepares and publishes International Standards for all electrical, electronic and related technologies and is establishing a new committee, TC 114, Marine Energy – Wave and Tidal Energy Converters, to develop International Standards for wave and tidal energy technology ([16]). Standards that will be developed by the new grouping of experts will cover the performance of tidal and wave energy converters, how these converters will plug into electricity grid systems, and how they should be tested.

-The WAVe Energy PLAnning and Marketing (WAVEPLAM) project has been started in 2008. Its purpose is to develop tools, establish methods and standards, and create conditions to speed up introduction of ocean energy onto the European renewable energy market, tackling in advance non-technological barriers and conditioning factors that may arise when these technologies are available for large-scale development, by means of a series of activities geared towards supporting creation of an ocean energy market ([17]).

-CORES (Components for Ocean Renewable Energy Systems) is an FP7 European collaborative research project focusing on new components and concepts for ocean energy converters ([18]). The project will concentrate on the development of new concepts and components for power-take-off, control, moorings, risers, data acquisition and instrumentation based on floating OWC systems. However, the components and concepts developed will have relevance to other floating device types. This project will run for a 3 year period, having commenced in April 2008. The new components and concepts will be tested on a floating OWC test platform at sea and these real, validated and verified results will be integrated into a holistic system model. This model will provide a Toolbox for wave to wire simulations of complete WEC systems. The Marine Institute Galway Bay Test site is location for the field test of the project. The Ocean Energy Buoy hull will be used as a test platform.

-The SuperGen program has started its second phase in 2007. The research priorities proposed in SuperGen Marine Phase 2 build on experiences and questions arising from early device tests, the deployment of prototype devices, the UKERC R&D road-mapping and DTI Protocol processes, and the outcomes of the original work programme. Phase 2 of the programme includes work on: device arrays and how these will influence local and regional environmental conditions; radical design approaches, which take into account new philosophies of design guidance; ensuring that numerical and physical design support is consistent and robust;

the challenges posed by design in mixed tidal and wave environments; system control in complex non linear and evolving environments; the complex challenges posed by fixing, mooring and recovery of marine systems; the economic challenges posed by the variable and intermittent nature of the marine resource; the sparse information available to predict and assess the long term reliability of marine energy systems and how an increased understanding of all of these issues can be best disseminated within the stakeholder community

-The Universities of Exeter and Plymouth have formed the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE). With an initial pump-priming fund of over £7.3 million from Southwest Regional Development Agency (SWRDA), PRIMaRE has enhanced its intellectual research capacity through the appointment of twelve new academic staff and a major investment in capital equipment and infrastructure. PRIMaRE is directly linked to Wave Hub, a new wave farm being established ten miles off the North Cornwall coast. This will provide a unique facility to evaluate arrays of wave energy conversion devices to generate power to the National Grid system. PRIMaRE is managed through a board consisting of representatives of the two universities and SWRDA ([19]).

It is expected that the work undertaken within the EquiMar project will receive beneficial inputs from the results of these different projects. The enhancement of contact and communication between the partners should aid the development and establishment of a common recognized framework for marine energy development.

1.4 THE EQUIMAR PROJECT

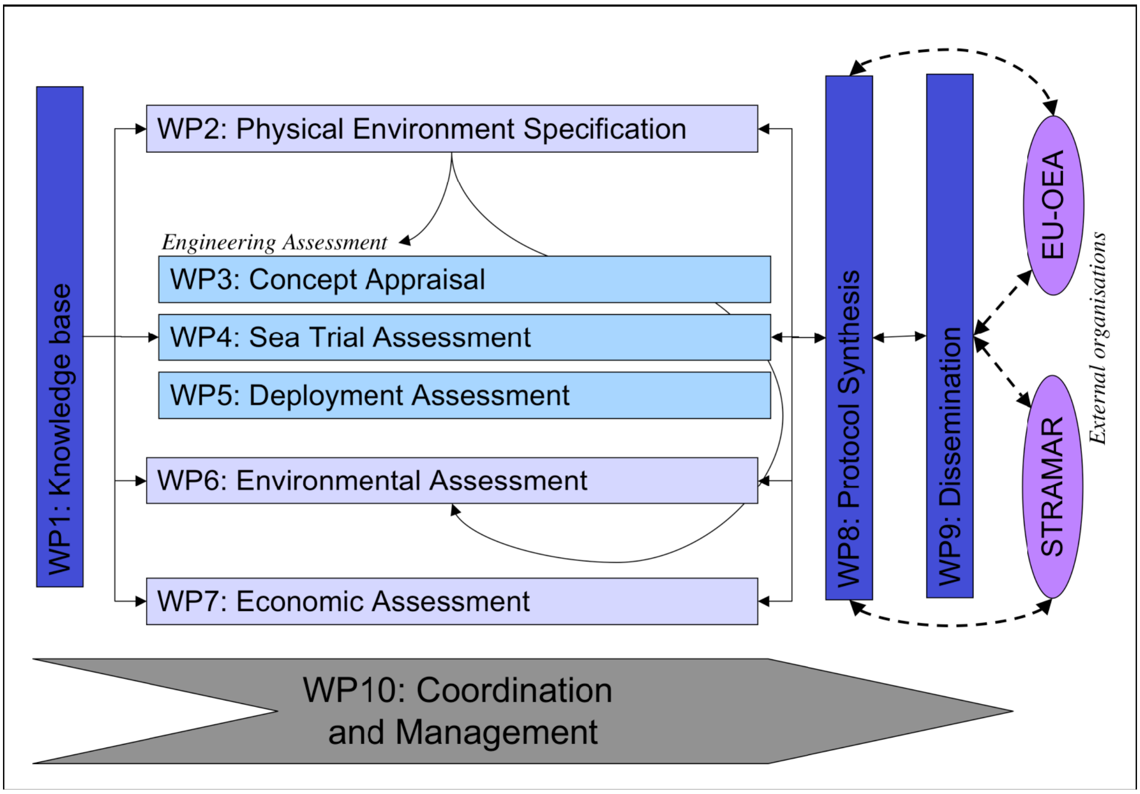

Figure 1.1 EquiMar project work package structure.

The EquiMar project is funded by the European Commission as part of its 7th Framework programme under the Energy topic. It is a collaborative research and development project involving a consortium of 23 partners and will run for three years from the 15th of April 2008. A list of the partners involved is given below:

1. **The University of Edinburgh (UEDIN)**, United Kingdom
2. **Fundación Robotiker (TECNALIA-RBTK)**, Spain
3. **University of Strathclyde (UOS)**, United Kingdom
4. **Electricité de France SA (EDF SA)**, France
5. **EU Ocean Energy Association (EUOEA)**, Belgium
6. **University of Exeter (UNEXE),** United Kingdom
7. **University College Cork (UCC)**, Ireland
8. **Wave Energy Centre (WAVEC),** Portugal
9. **The University of Manchester (UniMAN),** United Kingdom

10. **Southampton University (SOTON),** United Kingdom
11. **Institut Français de recherche pour l'exploitation de la mer (IFREMER),** France
12. **Consiglio nazionale delle ricerche: Istituto di Scienze Marine (CNR-ISMAR),** Italy
13. **Det Norske Veritas (DNV),** Norway
14. **Teamwork Technology (TT),** The Netherlands
15. **Pelamis Wave Power Ltd (PWP),** United Kingdom
16. **European Marine Energy Centre (EMEC),** United Kingdom
17. **Wave Dragon (WD),** Denmark
18. **Uppsala University (UU),** Sweden
19. **Sea Mammal Research Unit (USTAN),** United Kingdom
20. **Scottish Association of Marine Sciences (SAMS),** United Kingdom
21. **Feisty Productions Ltd (FPL),** United Kingdom
22. **Aalborg University (AAU),** Denmark
23. **Actimar (ACTIMAR),** France

The aim of EquiMar is to deliver a suite of protocols for the equitable evaluation of marine energy converters (based on wave or tidal energy). These protocols will harmonise testing and evaluation procedures across the wide variety of devices presently available with the aim of accelerating adoption through technology matching and improved understanding of the environmental and economic impacts associated with the deployment of arrays of devices. EquiMar will assess devices through a suite of protocols covering site selection, device engineering design, the scaling up of designs, the deployment of arrays of devices, the environmental impact, in terms of both biological & coastal processes, and economic issues. The protocols will be developed through a robust, auditable process and disseminated to the wider community. Results from the EquiMar project will establish a sound base for future marine energy standards.

The activity within the project is structured through the definition of ten different Work Packages (including the project management), each one covering a specific part of the project with specific objectives. Six of them (WP2, WP3, WP4, WP5, WP6 and WP7) are mainly focused on technical issues, WP1 is intended to build a knowledge base for marine energy systems, WP8 will deal with the synthesis of the protocols and the organization of the documentation while WP9 will focus on dissemination of the project activity through the wider community. Finally WP10 will include all the coordination and management issues.

A scheme of the structure of the project is given in figure 1.1.

1.5 WORK PACKAGE 1 – KNOWLEDGE BASE FOR MARINE ENERGY SYSTEMS

The work package 1 (“Knowledge base for marine energy systems”), led by ROBOTIKER-Tecnalia, aims at building a knowledge base for marine energy systems with respect to all the areas covered by the EquiMar project. Through the analysis of the relevant pre-existing information in the sector of marine energy and other similar industries it will provide important guidelines for other technical Work Packages. It will also be important to collect impressions and needs directly from the stakeholders that will address future work.

The objectives of this Work Package can be summarised into three main tasks:

-**Task 1.1** - To analyse results from previous National, European and International activities in the field of pre-normative research for marine energy. A global analysis report will be the outcome of this task: “Global analysis of pre-normative research activities for marine energy”.

-**Task 1.2** - To identify lessons learnt from other sectors, which can be applied to produce harmonised testing and assessment of marine energy extraction devices. This task will produce the report: “Recommendations from other sectors”.

-**Task 1.3** - To understand and take account of explicit stakeholders’ needs and practical constraints for matching different system designs to various marine environments. For that purpose a consultation of key stakeholders will be carried out. Different active and interested parties in marine energy, such as developers, investors, certification bodies, power distributors and policy makers, will be invited to contribute through a questionnaire to determine needs and constraints.

This report constitutes the principal result of the first task. It presents a general list and analysis of fundamental references for a preliminary database for assessment of marine energy systems.

This list includes mainly reports and protocols illustrating methodologies, recommendations and guidelines for the design, deployment and performance assessment of the converters. Some scientific papers, whose content was believed to be of general interest and application, have also been included. It was intended to recover information which is as generic as possible since the results of this work are expected to be applicable to any kind of marine energy device rather than to a specific class of them.

It has to be said, however, that, due to their more advanced state of development, wave and tidal energy devices were almost the only ones considered here, although much of the information reported might be useful for other kinds of emerging marine energy technologies.

This report is intended to provide an important input to the other Work Packages of the project and possibly to other stakeholders not directly involved in EquiMar even if it is not aimed at the presentation of any original result nor innovative technology. All the information contained in this document was obtained through a preliminary compiling and comparing activity, therefore the reader interested in acquiring deeper understanding of any particular subject outlined in this report is advised to consult the cited references.

1.6 STRUCTURE OF THE REPORT

In order to improve clarity and the comprehension, this report has been subdivided into different sections, which focus on different technical subjects.

Marine energy is a largely multidisciplinary field where competences and knowledge from several different research areas are needed. The choice of dividing the collected information into different subsections, depending on their content, will allow experts from different areas to easily find information relevant to their own field. Furthermore, the sections defined below are corresponding somewhat to respective work packages within EquiMar, helping to relate the contents to the future work that will be carried out.

Physical Environment and Resource Specification

In this chapter, all the relevant pre-normative research regarding marine environment specification will be addressed. We will consider mainly documents referring to the assessment of the environment as an energy source rather than design condition for load and structural estimations. This is due to the consideration that much of the standard procedures for wave and current loads calculation can be found in offshore engineering literature and norms and will be part of the content of Deliverable 1.2 “Recommendations from other sectors”.

Here the analysis will be focused on the resource assessment and description in order to estimate the power produced by marine energy devices and the different methodologies and parameters commonly used to represent the energy resource of waves, tides and currents.

Concept Appraisal, Device Modelling and Performance Assessment

This section will focus on existing procedures and methods in order to model marine energy device and validate concepts and preliminary technological choices. It will also provide background on existing recommendations for performance assessment techniques. This fundamental step in the development of a converter is usually taken both with numerical and physical testing. This chapter will address both cases.

Sea Trial Testing and Full-scale Design and Deployment

This chapter schematises the existing background information on general procedures and methodologies for advanced marine energy devices that are going to be deployed in real sea conditions. The subject will cover not only performance assessment and measurement but also recommendations on design issues and practical requirements.

Policy Issues And Environmental Impact Requirements

This section covers information relating mainly to non-engineering issues in marine energy. It will focus on existing recommendations about permitting and licensing procedures and environmental impact requirements.

Economic Assessment of Large Scale Deployment

This chapter will deal with cost accounting techniques and economic assessment procedures. The information recovered will be mainly aimed towards evaluating the profitability of marine energy.

1.7 REFERENCES

[1] IEA-OES, International Energy Agency – Implementing Agreement on Ocean Energy Systems – *Annual Report 2007* – 2007, available at: http://www.iea-oceans.org/_fich/6/IEA-OES_Annual_Report_2007.pdf

[2] HRMC – State *of the Art Analysis: A Cautiously Optimistic Review of the Status of Wave Energy Technology (Draft)* – 2008, WAVEPLAM Deliverable D2.1

[3] University of Strathclyde, Co-ordinated Action on Ocean Energy – *Tidal Renewable Energy Research, Development and Demonstration Roadmap* – 2007, see http://www.ca-oe.net

[4] VV.AA. – *WaveNet: Full report* – 2003, available at: www.wave-energy.net/Library/WaveNet%20Full%20Report(11.1).pdf

[5] DTI –*Wave and Tidal-stream Energy Demonstration Scheme – Definition document*– 2005, available at: http://www.berr.gov.uk/files/file23963.pdf

[6] Sustainable Energy Ireland (SEI) – *Ocean Energy in Ireland* – 2005, available at: http://www.sei.ie/index.asp?docID=-1&locID=1192

[7] HRMC – *Ocean Energy: Development and Evaluation Protocol. Part 1: Wave Power.* – 2003, available at: http://www.marine.ie/NR/rdonlyres/870BA9C2-B58E-4230-A4BD-5CE031A276DC/0/deweprotocol.pdf

[8] Previsic M., Siddiqui O., Bedard R. – *Economic Assessment Methodology for Wave Power Plants* – 2004, available at:

http://oceanenergy.epri.com/attachments/wave/reports/002_Rev_4_Econ_Methodology_RB_12-18-04.pdf

[9] EMEC – see http://www.emec.org.uk/national_standards.asp

[10] DNV for Carbon Trust – *Guidelines on design and operation of wave energy converters* – 2005, available at: http://www.dnv.no/Binaries/WECguideline_tcm28-181675.pdf

[11] Meyer NI, Nielsen K. - *The Danish wave energy programme second year status.* – 2000, Proceedings of the Fourth Wave Energy. Conference, Aalborg, pp. 10–18

[12] Mueller M.A., Jeffrey H., Wallace A.R., - *The UKERC Marine Renewable Energy Technology Roadmap* -2007, 7th European Wave and Tidal Energy Conference, Porto.

[13] UKERC - http://www.ukerc.ac.uk/ResearchProgrammes/FutureSourceofEnergy/FSWMarineRenewables.aspx

[14] SUPERGEN website: http://www.supergen-marine.org.uk

[15] Jeffrey, H.F, Mueller M and Smith G.H. - *An investigation of the Knowledge Base of the UK Marine Renewable Sector* - 2007, 7th European Wave and Tidal Energy Conference, Porto.

[16] IEC TC 114: http://www.iec.ch/dyn/www/f?p=102:7:0::::FSP_ORG_ID:1316

[17] WAVEPLAM website: www.waveplam.eu

[18] CORES website: http://www.fp7-cores.eu

[19] PRIMaRE website: www.primare.org

2. PHYSICAL ENVIRONMENT AND RESOURCE SPECIFICATION

2.1 INTRODUCTION

Environment specification is perhaps one of the first and most important phases that needs to be approached when a marine energy project is developed.

Before any technology can be successfully installed, it is obviously necessary to define the feasible location and identify with accuracy all the relevant physical parameters that will affect the behaviour and performance of the device. Any preliminary evaluation of the performance, profitability and opportunity of the deployment requires a detailed analysis of the energy resource of the area of installation and needs this analysis to be performed using recognized parameters and techniques and translated into results that can become input for the device performance assessment procedure.

Even though wave and tidal phenomena are often correlated and many general methodologies could be defined for both, the specification of the resource for wave and tidal energy devices is quite different in each case and based on a rather distinct theoretical and practical approach. Moreover, the two typologies of device present usually different dynamics and operational conditions and it could be argued that, on many occasions, feasible locations for wave energy deployment differ from those suited to tidal devices.

For all these reasons, the analysis of the existing pre-normative research in this subject will be separated between wave energy resource assessment and tidal energy assessment.

2.2 WAVE ENERGY RESOURCE ASSESSMENT.

Table 3 Existing guidelines and protocols for wave energy resource assessment

Author/Institution	Title	Year	Content
EMEC	The Assessment of the Wave Power Resource (DRAFT Guideline Standard)	2008	A general set of procedures for wave resource estimation, including suggestions on measurement instruments, models and data formats
WERATLAS group	WERATLAS	1997	Atlas of European wave energy resource. The approach is based on WAM numerical models
DTI	The Atlas of UK Marine Energy Resource	2004	An assessment of the UK resource. Methodology and suggestions for the compilation of resource database
Saulnier and Pontes (INETI)	Guidelines for Wave Energy Resource Assessment and Standard Wave Climate	2006	General outline of wave energy assessment parameters. Proposed standardised approach for resource representation

Wave modelling and climate specification has been a research subject for decades. A large amount of scientific literature can be found and sophisticated approaches have been addressed, particularly because of the requirements coming from the ship and offshore structures industry.

A comprehensive mathematical analysis of the waves and of the underlying physical phenomena can be found in several books. Two good reference books that summarize the theory behind waves and provide with a consistent explanation of spectral models and parameters have been written respectively by Tucker ([1]) and Goda ([2]). Another general textbook with an extensive description of the WAM modelling approach is the one by Komen et al. ([3]) while a guide freely available on the net is the publication from the World Meteorological Organization ([4]).

The specification of sea states is distinctly difficult. This is because the sea state at a given position is a random process consisting of effect occurring in time (from minutes to days) and over spatial scales from small to large (local generation up to seas propagating from considerable distances). This can lead to a wide range of specific sea states, particularly with regards to magnitude, frequency content and direction. This can then be radically modified by the site specific geometry, particularly the land masses and bathymetry.

Under the simplest approach, waves are usually represented as time series of the elevation of the sea surface. Considering samples of a defined duration (typically between 20 and 60 minutes), they are usually assumed to represent a stationary stochastic process and this allows to apply spectral frequency domain analysis.

Spectral models are nowadays widely used and applied to many fields in ocean engineering. Theoretical models can be defined for simulation purposes as well as for collection and representation of real sea measurements and several characteristics and information on the sea states can be given by a number of spectral parameters, mainly based on the statistical moments. It is useful to make a distinction between short-term statistics, usually based on the spectral representation, and long-term statistics, which are statistical data referring to the occurrence of spectral parameters over a long period (months or years).

The assessment of the energy resource of a site for device performance estimation generally depends, at the simplest level, on two parameters: the significant wave height (H_s) and the energy period (T_e). These data are usually represented in a scatter diagram, which represents the joint frequency of occurrence of these parameters within a particular period and height "bin" at a given site. This representation, usually determined by real measurements, often requires the assumption of a determined spectral shape (generally Bretschneider) to be useful for energy calculations and provide with an easy methodology for comparison of different sites (for example considering a specified wave energy device).

There is not yet any established standard for wave power calculation and resource estimation, however, this kind of approach is widely recognized and understood by most of the developers and researchers. The mathematical definition of these concepts is outlined in several documents. Saulnier and Pontes have produced a report named "Guidelines for Wave Energy Resource Assessment and Standard Wave Climate" ([5]) within the Wavetrain Research Network group, in which the mathematical formulation and derivation of these parameters is well defined and described as well as its relationship with the wave power. A useful source covering both frequency and time domain parameters is given by the International Association of Hydraulic Engineering and Research (IAHR [6]).

Another important factor to be taken into account during the resource assessment is the direction of the waves, especially if the device to be deployed is sensitive to this parameter. Apart from considering the mean wave direction given by measurements, a typical approach is to define a particular spectral formulation that accounts for the energy spreading along different angles or sectors.

The definition and application of directional spectra is still subject of research since several models have been proposed and no agreement has been reached on the most efficient one. Work on this issue has been done for years by the IAHR and an extensive summary of the various available methods and their formulation is found in [7].

Other effects still under research and that may have a consistent influence on the assessment are spectral bandwidth (the way the energy is distributed over frequency) and wave grouping (the presence of groups of waves travelling together). There is not yet agreement on how to model and represent these phenomena. Information on spectral bandwidth parameters can be found again in [5] and in a more detailed fashion in specific documents such as [8] and [9], while an interesting introduction to wave grouping estimation with an outline of the methodology possibly to be used for the individuation of the wave groups, based on the Hilbert-Huang transformation, has been given by De Bettencourt et al. ([10]). Other references treating extensively wave grouping are represented by scientific papers like [11], [12], [13], [14] and [15].

On what concerns the wave power resource assessment at a site, however, a preliminary draft guideline standard ([16]) has been produced by the European Marine Energy Centre (EMEC). This document firstly gives a brief outline and description of the measurements required and the type of tools necessary (Buoys, Acoustic current profilers, radars) and a general definition of the principal spectral and statistical parameters characterizing the wave energy resource. Also, a global prospect of the principal known wave models and a brief explanation of their use for wave power estimation together with some recommendations on the kind of information that should be included in a report are given.

A brief review of wave measurement technology has been done by Pitt ([17]). In this reference, four technologies (HF radar, ADCP, satellite measurements and wave buoys) among the most used for wave measurements are analysed and compared. Wave buoys are ideal for site measurements, providing good accuracy and data at typically half-hourly intervals. However, they are prone to loss or failure and continuous records of more than a couple of years are rare.

Satellite altimetry has the benefit of world-wide coverage and long records, although the data are spatially and temporally sparse (typical spatial separation 200km, interval between passes 20 days). The technique provides measurements of H_s that are documented to be of similar accuracy to wave buoys (e.g. Krogstad and Barstow [18]). Furthermore, it is possible to derive the energy period T_e to a useful resolution of around 1 second; estimates may then be made from the annual H_s and T_e scatter diagram of the energy that a given WEC would produce (Mackay *et al* [19]).

Wave climate database for several geographic location have been generated through the use of different numerical wave models. A result of this activity has been the implementation of global atlases. One remarkable result was the WERATLAS, whose standard procedure for the assessment of the wave energy resource off the Portuguese coast, using a hind-cast approach can be found in [20]. WERATLAS [21] is a European offshore wave energy resource electronic atlas developed within an EC contract that can be purchased by contacting the Instituto Nacional de Engenharia, Tecnologia e Inovação (INETI – www.ineti.pt). It contains a wide number of annual, summer and winter wave climate and wave power statistics for 85 points off the Atlantic and Mediterranean coasts of Europe. It is based mostly on results of the well known numerical wind-wave model WAM [22] implemented at the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, UK).

Another work specifically directed towards power estimation for extraction purposes is the Atlas of UK Marine Energy Resources ([23]), whose technical report includes an outline of the methodology utilised to describe the resource and some recommendations on how to compile and maintain a reliable marine energy database.

Finally, a mention should be made about the proposals on the use of standard wave climates that could represent large geographical areas through assembly and statistical analysis of wave data. One interesting and original work made on this subject is the master thesis of Burger ([24]), which deals with the attempt of designing and producing a standard procedure to define theoretical wave scatter diagrams using one simple figure, the power level, i.e. the estimated average available power per meter wave crest at a certain location. The ultimate result is a numerical tool that generates theoretical scatter diagram, based on the Ochi lognormal bi-variate distribution.

2.3 TIDAL ENERGY RESOURCE ASSESSMENT.

Table 4 Existing guidelines and protocols for tidal energy resource assessment

Author/Institution	Title	Year	Content
EMEC	Tidal Stream Resource Assessment Standard	2008	A comprehensive reference including detailed analysis of many aspects of tidal resource assessment
DTI	The Atlas of UK Marine Energy Resource	2004	An assessment of the UK resource. Methodology and suggestions for the compilation of resource database
Hagerman and Polagye (EPRI)	Methodology for estimating Tidal currents Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TISEC) Devices	2006	Application of a simple method to the estimation of tidal resources in North America. Useful for general preliminary resource analysis
SEI	Tidal & Current Energy Resource in Ireland	2004	A general work using existing sources to investigate the tidal potential in Ireland. Not very detailed and with approximate analysis but useful for preliminary estimation

Compared to waves, the tidal resource is more easily predictable and reliable. Typically, at a large scale, a database of measurements for tidal ranges over a period of one month is sufficient for a good prediction covering the entire life of a device. The estimation of the resource is usually based firstly on direct measurements of tidal elevations and/or current velocities. Afterwards a harmonic analysis allows distinguishing between different components and eventually defining a sample mean month for power evaluation.

A comprehensive treatment of the gravitational forces, meteorological effects and bathymetrical influences which drive tidal currents can be found in Pugh ([25]).

The European Marine Energy Centre (EMEC) has made publicly available a draft standard ([26]) schematising the steps and the different methods to perform a tidal stream resource assessment. Firstly it gives a structured subdivision in stages for a project development and then it deals with the information of the specific converters required for a resource assessment (as it is demonstrated that the presence of power extracting devices influences the upstream current speed). Another important aspect that is treated is the bathymetric survey with specific recommendations on this case and a good reference to other recognized standards (IHO). Tidal ranges have to be provided and can be found for many locations in specific documentation provided by public marine research institutes or oceanographic centres. The data for a defined location may possibly be derived by using commercially or freely available numerical software packages. Along with the ranges, current data should also be provided. Some descriptions of practical, environmental and permitting constraints are briefly shown while afterwards detailed recommendations on the estimation of current speeds by means of numerical models are given. Particularly useful is the indication of the grid resolution suggested for each stage of development. Such models should be calibrated and validated through in-situ measurements. The data analysis section provides also an outline of the extrapolation process from one typical month to a longer period. The final sections also deal with the estimation of the annual power output of an installed device and of the extractable energy from the site. Some considerations should be given, in this case, to the influence of power extraction, especially considering tidal farms, on the available resource. A consistent list of references regarding numerical hydrodynamic models is given at the end of the document.

A bathymetric survey is necessary for a detailed resource site assessment. A bathymetric database ([27]) with an available free package to visualize the data and a grid resolution of about 2 km, is constituted by the General Bathymetric Chart of the Oceans (GEBCO).

When a detailed analysis of the resource is needed for a global estimation of the annual power production, the characteristics of the device and the type of extraction mechanism should be known. This is mainly for an adequate estimation of the cross-section area of the channel but also with the aim of better defining the influence of the energy extraction on the channel flow parameters. Bryden et al. have shown the consistence of this effect with simple approximated models ([28], [29] and [30]).

There are several hydrodynamic models and codes provided to calculate and forecast flow conditions and velocity currents at a particular location (some of which are available on the Internet). This kind of approach is rather necessary when the assessment of the resource comes to the detail of a specified location and definition of the positioning and spacing of the devices comes into play. In this case the velocity profiles have also to be extrapolated for different depths and at different points of the grid, using as comparison and/or as boundary conditions the values given by real measurements. A sample of a possible usage of numerical hydrodynamic models to estimate and define the tidal speeds time series at a specific site and at different points of a grid has been given by Blunden and Bahaj ([31]).

Other research activities in this area have focused on the estimation of the available tidal resource at global regions with a definition of the most suitable geographic areas for device deployment.

In 2006 Hagerman and Polagye ([32]) have redacted for EPRI a general report that resumes several basic concepts about tidal energy and focuses on the estimation and assessment of the resource in North America. It gives links to internet database for tidal elevations and currents as well as to software for prediction of tidal current speeds. The methodology used for the mean annual energy resource calculation at different sites is presented along with the explanation of a simple method (based on the Bernoulli equation) for the extrapolation of the velocity profiles time series to different channel sections. An estimation of the power output given by an approximated turbine farm is given.

Another reference on these issues is represented by an interesting report ([33]), issued by SEI (Sustainable Energy Ireland), that evaluates the tidal energy resource in Ireland using a very efficient methodology. The estimation of the resource starts from the calculation of the potential through computational models and real measurements. Afterwards, a series of technological and practical constraints progressively reduces the value of the viable potential down to the selection of seven possible sites quantifying in 0.915 TWh/year the viable annual energy that could be produced in 2010, correspondent to a 2% of the Irish global electricity consumption.

Concerning the UK, fundamental work has been carried out within the preparation of the Atlas of UK Marine Renewable Energy Sources ([23]). The website includes some sample data describing tidal resource for the UK. The technical report includes an outline of the methodology utilised to describe the resource and some recommendations on how to compile and maintain a reliable marine energy database. Bathymetric information is given for the sea surrounding the UK coasts. The data for the tidal resource are based on different numerical models depending on the site location (2D models such as NEA and CS3 or 3D like HRCS that gives results for a 1.8 km grid resolution). Some additional description of important and involved parameters is provided at the end of the technical report.

A question that has raised consistent debate in the recent years concerns the interaction between surface waves and tidal currents as well as the understanding of the effect of the waves on device performance and structural loading regime. There is evidence that the induced motion beneath surface waves can produce significant cyclic loads on the blades of a marine current turbine ([34]), and influence the power output from the machine. Depending on the site exposure and the depth of immersion, it may be necessary to consider wave effects when characterising the performance of marine current turbines.

The works on resource assessment previously cited has also often neglected the importance of turbulence effects on marine current turbines. The presence of turbulence might imply different conclusions on site assessment. An insight on how to take into account these phenomena can be found in [35] and [36].

2.4 REFERENCES.

[1] Tucker M.J. and Pitt E. G.. – *Waves in Ocean Engineering: Measurement, analysis, interpretation* - Elsevier Ocean Engineering Series, 2001

[2] Goda Y.,- *Random seas and design of maritime structures* – World Scientific Publishing Ltd, 2000

[3] Komen, G. J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P. A. E. M. Janssen - *Dynamics and modelling of ocean waves* – 1994, Cambridge University Press

[4] World Meteorological Organization – *Guide to wave analysis and forecasting* – 1998, available at: http://www.wmo.ch/pages/prog/amp/mmop/documents/WMO%20No%20702/WMO702.pdf

[5] Saulnier J.B. and Pontes M.T. – *Guidelines for Wave Energy Resource Assessment and Standard Wave Climate* – Wavetrain Deliverable nº 4-7a, 2006.

[6] IAHR Working Group on Wave Generation and Analysis – *List of Sea-State Parameters* –Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 115, No. 6, 1989

[7] Benoit M., Frigaard P., Schäffer H.A. – *Analysing Multidirectional Wave Spectra: A tentative Classification of Available Methods* –Proc. IAHR Sem Multidirectional Waves Interact Struct. 27th IAHR Congress 1997, pp. 131-158

[8] Wolf D. - *Sensitivity of power output to wave spectral distribution* – 2002, Report for Seapower Ltd.

[9] Smith G H, Venugopal V and Fasham - *Wave Spectral Bandwidth as a Measure of Available Wave Power* – 2006, Proceedings of the 25th Offshore Mechanics and Artic Engineering, Hamburg.

[10] de Bettencourt J., Aguiar R., Pontes M.T. and Pires H.O. – *Standard Wave Data Sets and Wave Energy Device Performance Assessment* –Proceedings of the 5th European Wave and Tidal Conference, Cork 2003

[11] Medina, J. R. & Hudspeth, R. T. - *Review of analyses of ocean wave groups* – 1990, Coastal Engineering, **14**, pp. 515-542.

[12] Van Vledder, G. P. - *Statistics of wave group parameters* – 1992, Proc. 23rd Int. Conf. on Coastal Engineering, Venice, Italy, Vol. 1, New York, NY: ASCE, pp. 946-959.

[13] Masson, D. & Chandler, P. - *Wave groups: a closer look at spectral methods* – 1993, Coastal Engineering, **20**, pp. 249-275.

[14] Venugopal V and Smith G H - *The Effect of Wave period filtering and device tuning on wave power extraction* – 2007, Ocean Engineering,, Volume 33, pp 1120-1177

[15] Smith G.H., Venugopal V., and Wolfram J. - *Wave period group statistics for real sea waves and wave energy extraction* - 2006, Proc. IMechE Vol. 220 Part M: J. Engineering for the Maritime Environment

[16] EMEC Working Group – *The Assessment of the Wave Power Resource (DRAFT Guideline Standard)* – 2008, available at http://www.emec.org.uk/pdf/standards/wave%20resource%20assessment%20guidelines%20(draft%201).pdf

[17] Pitt, E.G. – *Review of wave measurement technology* – 2006, available at: http://www.wavehub.co.uk/

[18] Krogstad HE and Barstow SF - *Satellite Wave Measurements for Coastal Engineering Applications* - 1999, Coastal Eng., 37, 283-307

[19] Mackay EBL, Retzler CH, Bahaj AS, Challenor P - Wave *Energy Resource Estimation using Satellite Altimetry Data* - 2008, Proc. OMAE 2008, 27th Intl. Conf. on Offshore Mechanics and Arctic Engineering, 15-20 June, 2008, Estoril, Portugal

[20] Mollison D. and Pontes M.T. – *Assessing the Portuguese wave-power resource* – Energy 17 (1992), pp. 255-268

[21] The WERATLAS group - *WERATLAS Atlas of wave energy resource in Europe, Technical report* - 1997, EC JOULE Programme, ct. nº JOU2-CT93-0390.

[22] The WAMDI group - *The WAM model: A third generation wave prediction model* – 1988, Journ. of Phys. Ocean, vol. 18, 1775-1810.

[23] DTI – *Atlas of UK Marine Renewable Energy Resources* – 2004, available at: http://www.berr.gov.uk/energy/sources/renewables/explained/wind/page27741.html

[24] Burger – *Standardised Wave Data based on Power Level* – 2005, Master Thesis Delft University

[25] Pugh T.D. – *Tides, surges and mean sea-level.* – Wiley (1987), New York

[26] EMEC Working Group – *Tidal Stream Resource Assessment Standard* – (2008), available at: http://www.emec.org.uk/pdf/standards/TRA%20-%20Draft%201.pdf

[27] GEBCO – General Bathymetric Chart of the Oceans – available at http://www.gebco.net/data_and_products/gridded_bathymetry_data/

[28] Bryden I.G. and Couch S.J. – *ME1-marine energy extraction: tidal resource analysis* – Renewable Energy 31 (2006), pp. 133-139

[29] Bryden I.G. and Couch S.J. – *How much energy can be extracted from moving water surface? A question of importance in the field of tidal current energy?* – Renewable Energy 32 (2007), pp. 1961-1966

[30] Bryden I.G., Grinsted T. and Melville G.T. – *Assessing the potential of a simple tidal channel to deliver useful energy* – Applied Ocean Research 26 (2005), pp. 198-204

[31] Blunden L.S. and Bahaj A.S. – *Initial Evaluation of tidal stream energy resources at Portland Bill, UK* – Renewable Energy 31 (2006), pp. 121-132

[32] Hagerman G. and Polagye B. – *Methodology for estimating Tidal currents Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TISEC) Devices* – (2006), available at: http://oceanenergy.epri.com/streamenergy.html

[33] SEI (Sustainable Energy Ireland) – *Tidal & Current Energy Resource in Ireland* – available at http://www.sei.ie/getFile.asp?FC_ID=2296&docID=59

[34] Barltrop, N, Varyani, K S, Grant, A D, Clelland, D and Xuan Pham - *Investigation into wave-current interactions in marine current turbines* – 2007, Proc I Mech E Part A, Journal of Power and Energy, 221, 2, pp 233-242, Professional Engineering Publishing

[35] Kawanisi K. And Yokosi S. – *Mean and turbulence characteristics in a tidal river* – 1994, Estuarine, Coastal and Shelf Science, Vol.38, No. 5, pp. 447-469

[36] Lu Y., Lueck R.G., Huang D. – *Turbulence characteristics in a tidal channel* – 2000, Journal of Physical Oceanographics, Vol. 30, pp. 855-867

3. CONCEPT APPRAISAL, DEVICE MODELLING AND PERFORMANCE ASSESSMENT

3.1 INTRODUCTION

All the emerging technologies have to undertake a preliminary phase of validation and verification of their performances and operational principles, usually carried out by means of reduced-scale prototypes or analytical and computational models.

This is particularly true for marine energy technologies, where a good assessment and optimisation of the device is necessary at the very early stages since real sea tests are complicated and expensive.

At present no common practices are adopted to assess the performance and operational characteristics of conceptual and small prototype wave and tidal energy devices. Even though several methods and applications exist to assess the response of marine energy devices, there is no clear understanding of the kind of accuracy guaranteed and effort required by particular stages of the modelling and assessment procedure.

Some research has been focused in the past on the definition of protocols for development of marine energy projects (especially wave energy) or recommendations on the type of tests and scaling factors to be used. Mathematical and computational modelling is widely used as a primary assessment tool but it often relies more on device-specific assumptions and approaches rather than on standard procedures.

Due to the relative difference of the concepts, it is unlikely for a unique standard modelling approach to be identified but some requirements on the representation and accuracy of the results as well as considerations on the validity of the available approaches can be provided.

3.2 TANK TESTING PRACTICES.

Table 5 Existing guidelines and protocols on tank testing practices

Author/Institution	Title	Year	Content
IEA-OE	Ocean Energy, Annex II Report 2003 (Development of recommended practices for testing and evaluating ocean energy systems)	2003	Report on methodologies and practices for wave energy devices testing. Perhaps out-dated: the practices are largely based on early-stage devices
HRMC-UCC	Ocean Energy: Development and Evaluation Protocol. Part 1: Wave Power	2003	Global protocol on general development route. Recommendation on choice of the scale, model structure and other practical issues
EMEC	Wave Testing Standards for Tank Testing of Wave Energy Converters – Scoping Document v3	2007	Not a real protocol. It represents only a table of contents to be addressed in the future work
University of Southampton for BERR	Tidal-current Energy Device Development and Evaluation Protocol	2008	Protocol on tidal technology development based on five stages with assessment of economical indicators. It includes a review of concepts and variables involved in tidal device performance assessment
Payne (University of Edinburgh)	Guidance for experimental tank testing (Draft)	2008	Recent work containing information on physical modelling and measurement techniques but still at draft stage

Concept appraisal is usually the first step a developer is required to consider before the start of a project. It can be summarised as a phase where a preliminary qualitative and quantitative analysis of the performance of the device is performed.

The proof of a concept can be carried out through different approaches: typically the simplest and most reliable way is to conduct a series of physical experiments on a small-scale model. For marine energy converters, this is usually done in tanks or channels, where environmental conditions can be simulated at the appropriate scale.

There are a relatively large number of laboratory facilities fit to ocean energy testing in Europe. The International Energy Agency (IEA) issued a report in 2003 ([1]), that includes a list of the principal wave tank and laboratory facilities located in the countries belonging to the IEA-OE by the publication date with a detailed description of the dimensions and capabilities.

Testing procedures are generally specific for each laboratory and there is no standardised practice for marine energy converters tank testing. The IEA report, however, provides with a brief introduction to scaling rules and wave modelling, with a description and explanation of the typical parameters used for the wave representation and description and a set of representative sea states recommended for laboratory testing of the converters. The main part is devoted to the definition of recommended experiments for wave energy converters. It is suggested to test the device to different kind of spectrum (Pierson-Moskowitz and JONSWAP) and to consider directionality if required by the particular type of device. For instance the influence of the wave period is tested using PM spectra while JOWNSWAP representations are used for bandwidth and spectral shape. Suggestions are also given for duration of the tests (60 minutes in full scale) and for other conditions to be tested for design loads (such as fatigue and extreme waves). Another chapter is dedicated to measurements, with a brief explanation of different power extraction mechanism and the kind of quantities and units involved. Some information, although brief and not exhaustive, is also provided on real sea prototype testing. A general procedure for performance assessment and optimisation based on a preliminary cost analysis is also given. Much of the information contained within this report is based on the principles defined by the Danish Wave Energy Programme ([2]) run between 1997 and 2001 and most of the guidelines are specifically directed to wave energy converter developers rather than tidal devices.

The Hydraulic Marine Research Centre (HMRC) of the University of Cork has produced a development and evaluation protocol ([3]) in 2003, mainly devoted to the definition of a standard procedure for the development and contemporary assessment of wave energy concepts and projects but including several recommendations on tank testing and modelling procedures. The protocol is based on similar procedures defined by NASA and used in other engineering research programmes and is primarily focused on the design and optimization of the device rather than on other important issues such as resource assessment, licenses and permissions and others.

The strategy is divided in five main phases:

-1. Validation Model: This first stage is aimed at the simple proof of the concept and for this scope just small-scale (1:25 to 1:100) simplified models can be used in order to ease changes and modifications aimed at optimisation. Three different steps within this phase can be distinguished: Concept Verification, Performance and Response, Device Optimisation

-2. Design Model: A medium scale (1:10 to 1:25) model is tested in order to define the behaviour of a more realistic PTO mechanism. The accuracy of the model, intended as good representation of the expected prototype design should be proven by naval architecture analysis and preliminary extreme wave tests and mooring response analysis should be performed in this stage.

-3 Process Model: The recommended scale for this phase is between 1:3 and 1:15. In this case two options are feasible: a very large-scale testing facility or a sea trial benign site with natural weather conditions adequate to the device scale. This is the moment when actual PTO and mooring components can be tested more realistically.

-4 Prototype Device: Provided with realistic performance data and a detailed estimation of manufacturing costs and maintenance requirements, the choice for a full-scale prototype should be made now, assuming that the previous evaluation has come to a positive result. Grid connection should be included at one point although not strictly necessary in the first steps of the prototype testing.

-5 Demonstration Device: The final phase that will come after having proven the effectiveness and reliability of the full-scale prototype. Electricity sale and grid connection will be an important issue at this time.

The information on each phase includes also estimation of the required budget and of the kind of measurements, tools and components that might be required for each step. There is also a general outline of the kind of computer simulations that should accompany the experimental modelling.

Even though much of the recommendations could be considered valuable for other kind of devices, it has to be said that the HRMC protocol cited here refers to wave energy converters, particularly of the floating type.

A similar work has been recently carried out for tidal-current devices by the Sustainable Energy Research Group (SERG) of the University of Southampton, under commission of the UK Department for Business, Enterprise and Regulatory Reform. A main result is a draft protocol ([4]) based on a stage-gate approach for technology development with a total of five stages and gates. Stages represent development activities and gates are point of evaluation of those activities.

The whole process was broadly based, as for the previous case, on the approach defined for the Technology Readiness Assessment (TRA) developed by NASA to manage the development of technology as part of the space programme, breaking down a system into subsystems and components each to be developed in a number of stages. The ultimate goal at each stage of development is to assess whether the production tidal-current energy device is technically and economically viable, with increasing certainty at each stage. The five stages, described by flowcharts within the document, are:

-Theoretical and computational studies

-Scale model testing in an intermediate sized facility

-Scale model testing in a large facility

-Full scale prototype testing

-Demonstrator testing

The protocol includes a background description of previous published guidelines and similar works. It is interesting to note that one of the claimed aims of this protocol is the technology assessment based on cost-effective and economical efficiency analysis with the definition of minimum threshold performance values to be reached for progressing to the subsequent stage. This is perhaps an approach more oriented to investors and utilities rather than the previous references cited before, whose end-users were expected to be device developers and the research community.

The European Marine Energy Centre (EMEC) is also working on standards for testing of wave energy converters in tanks. A draft document ([5]) has been already disseminated but it represents a general outline and structure of the future document and does not contain yet any specific recommendation or indication.

The University of Edinburgh has produced guidance for experimental tank testing through the SuperGen Marine consortium. This document [6] is at late draft stage and discusses physical model considerations (e.g. scaling), measurement techniques and wave generation methods.

3.3 DEVICE MODELLING.

Table 6 Existing guidelines and protocols on modelling methodologies

Author/Institution	Title	Year	Content
McCabe (Lancaster University)	An Appraisal of a Range of Fluid Modelling Software	2004	Report on existing commercial fluid modelling software packages with details on the capabilities and the limitations of each tool. Gives a good overview of the availability but does not analyse the applicability to marine energy sector

Another possible approach for concept proof and optimization of the device is the mathematical and numerical modelling of its dynamics and interactions with the environment.

Due to the existing differences between the various concepts, neither standard theoretical assessment procedures nor globally applicable computational tools have been identified for wave or tidal technologies.

Marine energy technologies can be categorised depending on the operating principle responsible of the energy extraction. Wave energy technologies are usually divided between:

- Oscillating Water Columns (OWC)
- Overtopping Devices
- Wave Activated Bodies

Tidal stream devices are instead classifiable in four groups:

- Horizontal axis systems
- Vertical axis systems
- Variable foil systems
- Venturi based systems

The assumptions and approaches used to model each of this kind of devices are generally different and might be device-specific even inside a defined category.

Some common modelling bases, however, can be found taking into account the interaction between the converter and the sea, which is modelled under the same assumptions in several cases.

Main references for the modelling of marine energy devices are the books from Newman ([7]) and Faltinsen ([8]). Fundamental theoretical and analytical results for wave energy have been given by Falnes ([9]). The modelling of many tidal technologies can also be linked to marine propellers technology ([10]).

Theoretical formulation for loads and motions of marine energy converters are available only for simple geometries and flows. With the constant development of more and more powerful computers, numerical computation of these quantities has become consistently quick and reliable. In the recent years many commercial computational codes have been released for the simulation of fluid phenomena.

Within the SuperGen programme, McCabe published in 2004 an analysis ([11]) of a list of different commercial computer packages that can be used for the calculation of the loads and the motions of the bodies composing marine energy converters. It is an interesting study that focuses on the different capabilities of every package but lacks a detailed comparison of the results and the accuracies that each of the software provides for single cases. This reference distinguishes between hydrodynamic analysis and CFD software, giving also a brief outline of the theoretical background on which these packages are based. It is, however, not clear which type is usually needed for which application and whether hydrodynamic and CFD programs can be used for the same practical device in different phases or, for instance, for different scales.

Typically for floating wave energy devices the hydrodynamic analysis is based on the potential flow theory and linear water wave theory with the subsequent definition of proper hydrodynamic coefficients for the estimation of the wave loads. These coefficients can be found in literature for simple cases but are more usually computed with the use of Boundary Element Method software packages, such as WAMIT ([12]) or AQWA ([13]). The estimation of the performance and the analysis of the dynamics are carried out through two different types of approaches: frequency-domain and time-domain methods. The former is relatively easy to implement and is based on the assumption of linear relationship between motion amplitudes and loads. It is usually applied on a preliminary modelling phase when a quick evaluation of a configuration is needed. The latter makes use of the Cummins equation ([14]) and allows non-linear models with the possibility of taking into account a detailed Power Take-Off representation and a complete wave-to-wire model. There are several cases showing the application of these tools in literature (see [15] and [16] for examples) but, although some general procedures might be defined, the results and outcomes of these works are dependent on the device considered and on a series of assumptions that might have a different impact on each case and there is no explicit reference to any standard guideline or recommendation. An investigation on the suitability of different time-domain formulations applied to marine structures under a general approach was given by Taghipour et al. ([17]).

For extremely severe wave loading, the assumptions of linear wave theory on which these models are based are not valid and nonlinear wave models are required. Although detailed guidelines are not yet available, a comparison of modelling tools for this purpose from the Plymouth University (with experimental validation against heaving bodies and the Pelamis) will be available in 2009.

The choice of the adequate modelling approach appears to be, therefore, still strongly dependent on the technology considered. The same applies to other types of wave energy devices such as OWCs for which the numerical modelling approach is usually similar to the one applied to floating devices (see [18]). Different approaches are required for overtopping devices for which characterisation relies more on physical modelling and tank testing.

Some developers, like Pelamis ([19]), have defined an internal procedure for numerical model testing with the usage of internally developed and commercial codes.

Concerning tidal current turbines, a lot can be learned from the technology transfer from wind turbines and ship propellers: The basic performance of a marine current turbine, like a wind turbine, can be modelled satisfactorily using blade element momentum (BEM) theory (see [20]) but many uncertainties are due to the account for turbulence effects in unsteady flow conditions ([21]) and the possible interaction with surface waves, as mentioned previously related to resource assessment. The sensitivity of performance and loading of marine current turbines to these effects has been subject of recent studies such as the one from McCann ([22]). However, much of the ‘generic’ work on horizontal axis tidal stream devices concerns open-bladed horizontal axis device (such as MCT) while enclosed blade-tip devices (Cleancurrent, OpenHydro, Lunar, etc) have received less attention.

Structural loads can often be computed through the use of existing commercial software developed for other marine industry sectors. One such case is represented by ORCAFLEX ([23]), a software package for time-domain analysis of offshore structures including cable dynamics, particularly suitable for mooring and riser design. Other commercial program exist (MOSES [24] and OPTIMOOR [25] for example) but all of them have been defined for different applications and cannot take into account the influence of mooring on power extraction and are therefore not very flexible for marine energy devices.

3.4 PERFORMANCE ASSESSMENT OF THE MODEL.

Table 7 Existing guidelines and protocols on model performance assessments

Author/Institution	Title	Year	Content
Hagerman and Bedard (EPRI)	E2I EPRI Specification: Guidelines for Preliminary Estimation of Power Production by Offshore Wave Energy Conversion Devices	2004	Outline of the classical standard procedure to produce estimation of power production of offshore wave energy converters based on specific location climate. Generic but easily applicable
Hagerman and Polagye (EPRI)	Methodology for estimating Tidal currents Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TISEC) Devices	2006	Methodology of power estimation for tidal current devices rather analogue to the one applied to wind turbines.
Smith and Taylor (Heriot-Watt UEDIN for DTI)	Preliminary Wave Energy Device Performance Protocol	2007	Outline of requirements for performance assessment detailed on records and reporting format. Methodologies and recommendations for power estimators but does not point to a specific procedure
University of Edinburgh for DTI	Preliminary Tidal Current Energy: Device Performance Protocol	2007	Outline of requirements for performance assessment detailed on records and reporting format. It accepts the wind analogy as assessment technique but does not address the problems of waves and turbulence effects

Performance assessment is the principal criterion for the evaluation of a marine energy converter at a preliminary stage of the design.

Comparison and selection of different concepts, geometries and components is usually carried out through the estimation of the expected produced power, although a basic qualitative economical assessment should be considered from the beginning.

Methodologies and procedures applied for the assessment should be usually uniform and very well specified to avoid misinterpretation and controversy.

This is particularly important when different technologies are being compared for an investment decision.

In this section we refer to general procedures for performance assessment, considered from the mathematical point of view. Some different recommendations are given for devices in open sea testing, whose performance assessment procedures are described in the next chapter.

Few studies on quantitative comparison and analysis of marine energy devices have been published. Researchers from EPRI (Electric Power Research Institute) have published a report in 2004 ([26]) that illustrated an assessment and evaluation of different concepts and wave energy devices based on a multi-criteria analysis. Although somewhat outdated, the methodology there outlined is interesting and useful.

The criteria considered were: technical issues (structure, power take-off, mooring, survivability, grid integration, performance, operation and maintenance, deployment and recovery and design tools), cost (the estimation of it can be traced also in another report), device developer criteria and state applicability (includes design advantages and disadvantages). The screening of the developers was performed in order to find the most mature technologies for comparison and was based on a survey.

Subsequently the technologies were compared based on two possible deployment scales: a 1500 MWh pilot plant and a fully commercial 300000 MWh power plant. The implementation location was assumed to be a reference station in Oregon and the power production estimation was based on capture width data provided by the developers. Out of eight considered technologies, only one was believed to be acceptable, at its stage of development, for application in a pilot plant.

Costs and technical difficulties were also evaluated through specific methods, to be addressed in the next sections. The procedure applied to estimate the power production in this report was described in another document ([27]), representing an outline of the classical standard procedure to produce estimation of power production of offshore wave energy converters based on specific location climate. The typical parameter used for device performance was the capture width ratio (practically the capture width divided by the width of the device) while the wave data were represented by means of the significant wave height and peak period scatter diagram. This can be considered as an almost standard procedure, although, as it was mentioned in the previous chapter, most of the wave energy developers usually prefer the use of the energy period instead of the peak period.

EPRI defined guidelines for power estimation of tidal devices also in the already cited report ([28]) on tidal resource assessment. Tidal turbines performance is generally represented with a power curve dependent on the current velocity. The produced power, proportional to the cross-section area and the average of the cube of the velocity, will be zero below a determined cut-in speed and will not exceed the rated value for the turbine when the speed exceeds a rated value. The methodology is rather analogue to the one applied to wind turbines and software tools such as Garrad Hassans Bladed have been adapted to apply to Tidal devices [29].

The UK Department of Trade and Industry (DTI) issued in 2007 two preliminary protocols on performance assessment for wave ([30]) and tidal energy ([31]) devices. These protocols outline a series of requirements and operations to be fulfilled to apply for funding to the Marine Renewable Deployment Fund (MRDF). In order to receive the capital expenditure to support installation and further revenue support during generation, the performance of the devices should be measured and recorded as described in this document. The specifications refer to open sea measurements but guidelines on the mathematical representation and reporting of the performances can also be found in two accompanying documents.

A supporting commentary on wave energy devices ([32]) clarifies the reasons for some choices and the difficulties behind the definition of some measurements and gives an interesting explanation of the usefulness and the limits of the power matrix. It has to be noted, in fact, that more power matrixes should be created for different bandwidths and directionalities one way being the generation of matrices for maximum, minimum, average and standard deviated power production.

A feedback from developers on the protocol for tidal energy has also been produced ([33]): It is interesting to note that the wind analogy for the estimation of the resource and the definition of a “power curve” has been widely accepted by the participants to the process. Concern has also been expressed regarding the fact of not taking into account the likely impact of the device on the local underlying resource. There is also some doubt on how to consider the effect of the waves (wave-current interaction) on the device performance.

3.5 REFERENCES.

[1] IEA (International Energy Agency) – *Ocean Energy, Annex II Report 2003 (Development of recommended practices for testing and evaluating ocean energy systems*) – 2003, available at:
http://www.iea-oceans.org/_fich/6/IEA-OES_Annex_II_2003_(2406).pdf

[2] Meyer NI, Nielsen K. - *The Danish wave energy programme second year status.* - Proceedings of the Fourth Wave Energy. Conference, Aalborg, 2000, pp. 10–18

[3] HRMC (University College of Cork) – *Ocean Energy: Development and Evaluation Protocol. Part 1: Wave Power.* – 2003, available at: http://www.marine.ie/NR/rdonlyres/870BA9C2-B58E-4230-A4BD-5CE031A276DC/0/deweprotocol.pdf

[4] SERG (University of Southampton) – *Tidal-current Energy Device Development and Evaluation Protocol (Draft)* – 2008, Department for Business, Enterprise & Regulatory Reform

[5] Nares NDSL for EMEC – *Wave Testing Standards for Tank Testing of Wave Energy Converters – Scoping Document v3* – 2007, available at: http://www.emec.org.uk/pdf/standards/Wave%20Tank%20Testing%20Standards%20Scope%20%20(v3).pdf

[6] Payne G. - *Guidance for experimental tank testing (Draft)* – 2008, SuperGen Marine, The University of Edinburgh

[7] Newman J.N. - *Marine Hydrodynamics* – 1977, Cambridge: MIT press.

[8] Faltinsen O.M. – *Sea Loads on Ships and Offshore Structures* – 1993, Cambridge University Press.

[9] Falnes J. - *Ocean Waves and Oscillating Systems: Linear Interactions Including Wave-Energy Extraction*- 2002, Cambridge University Press.

[10] Carlton J.S. - *Marine propellers and propulsion* – 1994, Butterworth Heinemann.

[11] McCabe, A, P, – *An Appraisal of a Range of Fluid Modelling Software*– 2004, Supergen Marine Workpackage 2, Lancaster University.

[12] WAMIT: www.wamit.com

[13] AQWA: http://www.ansys.com/products/aqwa.asp

[14] Cummins, W.E. - *The Impulse Response Function and Ship Motions* - 1962, Schiffstechnik 9 (1661), pp. 101-109.

[15] Falcão A.F.deO. - *Modelling and control of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator* - 2007, Ocean Engineering, 34, pp. 2021-2032

[16] Josset C., Babarit A., Clément A.H. - *A wave-to-wire model of the SEAREV wave energy converter* – 2007, Proc IMechE, Part M, Volume 221, Number 2 / 2007

[17] Taghipour R., Perez T., Moan T. - *Hybrid Frequency-Time Domain Models for Dynamic Response Analysis of Marine Structures* -2008, Ocean Engineering, Volume 35, Issue 7, Pages 685-705

[18] Brito e Melo A. M. C. F. de. - *Modelação e Pré-dimensionamento de Centrais de Coluna de Água Oscilante: Aplicação à Central de Energia das Ondas do Pico, Açores* – 2000, PhD Thesis, Instituto Superior Técnico, École Centrale de Nantes, 2000.

[19] Henderson R. – *Case Study: Pelamis* – 2007, Ocean Wave energy: Current Status and Future Perspectives (Chapter 5), ed. João Cruz, Springer.

[20] Batten, WMJ, Bahaj, AS, Molland, AF and Chaplin, JR - *The prediction of the hydrodynamic performance of marine current turbines* - 2008, *Renew. Energy*, Vol 33, pp1085-1096

[21] Gant S., Stallard T. – *Modelling a Tidal Turbine in Unsteady Flow* – 2008, Proceedings of the Eighteenth ISOPE, Vancouver, July 6-11, 2008

[22] McCann G. N. – *Tidal current turbine fatigue loading sensitivity to waves and turbulence* – a parametric study – 2007, Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal

[23] ORCAFLEX: http://www.orcina.com/

[24] MOSES: http://www.ultramarine.com/g_info/moses/moses.htm

[25] OPTIMOOR: http://www.tensiontech.com/

[26] Previsic M., Bedard R. and Hagerman G. – *E2I – EPRI Assessment – Offshore Wave Energy Conversion Devices (Report E2I EPRI WP-004-US-Rev 1)* – 2004, available at: http://oceanenergy.epri.com/attachments/wave/reports/004_WEC_Device_Assess_Report_Rev1_MP_6-16-04.pdf

[27] Hagerman G. and Bedard R. –*E2I EPRI Specification: Guidelines for Preliminary Estimation of Power Production by Offshore Wave Energy Conversion Devices* – 2004, available at:
http://oceanenergy.epri.com/attachments/wave/reports/001_WEC_Power_Production.pdf

[28] Hagerman G. and Polagye B. – *Methodology for estimating Tidal currents Energy Resources and Power Production by Tidal In-Stream Energy Conversion (TISEC) Devices* – 2006, available at: http://oceanenergy.epri.com/streamenergy.html

[29] Garrad-Hassan – *Tidal Bladed Manuals*, 2008.

[30] Smith G. and Taylor J., Heriot-Watt University and University of Edinburgh for DTI – *Preliminary Wave Energy Device Performance Protocol.* – 2007, available at*:* http://www.berr.gov.uk/files/file38989.pdf

[31] University of Edinburgh for DTI –*Preliminary Tidal Current Energy: Device Performance Protocol* – 2007, available at: http://www.berr.gov.uk/files/file38991.pdf

[32] Smith G. and Taylor J., Heriot-Watt University and University of Edinburgh for DTI – *Preliminary Wave Energy Device Performance Protocol. – supporting commentary* – 2007, available at*:* http://www.berr.gov.uk/files/file38990.pdf

[33] University of Edinburgh for DTI –*Preliminary Tidal Current Energy: Device Performance Protocol*, *response to feedback from 19th July workshop and consultation* – 2007, available at: http://www.berr.gov.uk/files/file38993.pdf

4. SEA TRIAL TESTING AND FULL-SCALE DESIGN AND DEPLOYMENT

4.1 INTRODUCTION.

After several scaled-models and validations of the concept and of the various design choices, every marine energy converter needs to be tested in real sea conditions to prove its maturity and its feasibility for commercial exploitation.

The open sea environment determines an unavoidable loss of control on the testing and evaluation procedures particularly on what concerns the energy flux input, which could be influenced by natural random causes, which are sometimes not easily predictable. This means sea trial schedules and analysis methodologies must be very carefully planned and rigorously followed if the performance and behaviour of the machines are to be verified and improved under real operating conditions.

Since the environmental conditions will be possibly very close or even the same as the ones considered in the preliminary plan, the selection of components and the detailed design of the converter should be defined at this stage, including technical aspects such as manufacturing and reliability. On-board safety requirements have also to be taken into account in the construction and maintenance of the device.

No internationally recognized standard has been produced yet in this field but a lot of effort has been dedicated to this area in the recent years with some consistent protocols being published and making reference, for particular technical issues, to existing standards for offshore and wind energy industry. As mentioned before, Det Norske Veritas (DNV) has produced, in collaboration with the Carbon Trust, the Guidelines for Design and Operation of Wave Energy Converters which provides guidance on how existing offshore standards may be applied to specific areas of wave energy converters. DNV has also started a certification process which is defined in the document OSS-312 (published in October 2008). The International Electrotechnical Commission (IEC) after the formation of Technical Committee (TC) 114: *Marine Energy – Wave and Tidal Energy Converters,* has defined a work plan on the assessment of performance of wave energy converters in open sea.

This chapter addresses existing guidelines for the engineering of marine energy devices and all the related aspects to the measurement and assessment of the performance in open sea.

4.2 PERFORMANCE ASSESSMENT IN OPEN SEA.

Table 8 Existing guidelines and protocols on open sea performance assessment

Author/Institution	Title	Year	Content
EMEC	Performance Assessment for Wave Energy Conversion systems in Open-sea Test Facilities	2005	Comprehensive list of recommendations for performance assessment including annexes on theoretical basis. Quite general. It does not consider device and site variability
Smith and Taylor (Heriot-Watt UEDIN for DTI)	Preliminary Wave Energy Device Performance Protocol	2007	Outline of requirements for performance assessment detailed on records and reporting format. Similar approach of EMEC on use of power matrix.
Swift R.H., ABPMer (EMEC)	Performance Assessment for Tidal Energy Conversion systems (TECS) in Open Sea Test Facilities	2008	Recommendations and requirements for performance assessment of tidal devices. It relies on the wind analogy for power curve representation. Not taking into account waves or turbulence.
University of Edinburgh for DTI	Preliminary Tidal Current Energy: Device Performance Protocol	2007	Performance assessment requirements detailed also on instruments placement and reporting format. Includes suggestions for resource assessment within the deployment site. It accepts the wind analogy as assessment technique but does not address the problems of waves and turbulence effects

The primary objective of sea trial tests is the measurement and assessment of the power performance of the device. Data are sampled and collected in order to characterize the behaviour of the system and eventually compare it with previous results obtained numerically or with small-scale models.

In recent years, several developers have been carrying out open sea tests of their technologies in different sites. In some of these places, through the support of local and regional governments, facilities and research centres have been purpose-built to test marine energy device and have started to apply specific locally developed procedures and practices.

4.2.1 Wave energy conversion performance assessment

The European Marine Energy Centre (EMEC), based in Orkney, UK, was the first institution established for this purpose and is consistently involved in standardization process for marine energy development. In 2005 it issued a draft standard ([1]) for performance assessment of Wave Energy Converters (WECs) which is the current reference document for the IEC working team.

This standard consists of a procedure for measuring the power performance characteristics of a single WEC and applies it to all WECs of whatever technology, situated in open sea and connected to the electrical power grid. The power performance characteristics are based on the estimation of the measured power matrix and the annual energy production.

Within the document detailed guidelines on different issues are given:

-Test conditions: A meteorological station and a bathymetry survey have to be provided for the site. Actual sea-state data should be measured by a wave-buoy and the collected data should allow the estimation of the directional spectrum. Sea-states should be represented on a scatter diagram. The effect of the distance of the wave measuring device from the WEC has to be taken into account.

-Test equipment: The net electric power of the WECs shall be measured using a power measurement device (power transducer) and be based on measurements of current and voltage on each phase. Current streams and sea water density variations should also be taken into account (values for the tolerated uncertainties are given) and the status of the converter should be continuously monitored.

-Measurement procedure: Recommended data sampling rate is of at least 2 Hz. Selected data sets shall be based on 30-minute periods. Corrections of the data for tidal stream velocity should only be attempted when clear empirical evidence is known. Corrections for seawater density should be to a standard of 1025 kg/m^3. Distinction for wave direction and uni- or bimodal spectra should also be made whenever a device sensitive to directionality is tested.

-Derived results: The measured power performance is defined based on the “method of bins” with a wave height increment of 0.5 m and a period increment of 1.0 second. A simple single power matrix can be used anytime that the WEC is not sensitive to direction or the directional spectra characteristics do not vary significantly at the test site. Where a power matrix is defined, the annual energy production can be estimated. If the measured power matrix does not include data up to cut-off wave height and period, the power matrix shall be extrapolated from the maximum measured wave height for a given period. A power coefficient can also be defined through the determination of two parameters (absorption length and sensitivity to frequency). Such coefficients can be estimated also by means of a LS fitting to the results for each bin.

-Reporting format: A brief description of the expected report format, including a general scheme of each section, a list of the figures to be included and the kind of information required.

-Annexes: These contain additional information, especially technical background to wave spectra and a description of the assumptions made in order to compute a generic power output for a survey of the Orkney site. There is also an interesting short appendix that describes the power estimation from wave measurements procedure.

As mentioned before, the UK Department of Trade and Industry (DTI) issued in 2007 two preliminary protocols on performance assessment for wave and tidal energy devices, defining a series of requirements and operations to be fulfilled to apply for funding from the Marine Renewable Deployment Fund (MRDF).

Under the wave energy protocol ([2]), the device developer is expected to provide several documents during the whole extension of the project. Firstly, prior to the commencement, global project information on the physical nature of the location and the information on the placement of the devices and the measuring instruments is needed. Then, continuous wave recording and monitoring of the produced power should be carried out. Sea state and average device performance should be computed every half-hour period. The cumulative records of these measures should be collected in a report and delivered every year.

Many guidelines and recommendations are similar to the ones defined in the EMEC standard: The project information should include an assessment of the bathymetry, mean wave direction and tidal ranges, deployment plans and locations, the declared performance in form of a power matrix and also an assessment of the influence of the device under other spectral parameters (such as bandwidth and directional spreading).

Concerning the measurement of the resource, the DTI protocol suggests utilising a half-hour period for averaging quantities. The power densities and other quantitative parameters are advised to be computed based on a frequency-domain spectrum representation. The wave measurements should be given by a wave-buoy. Details are given on the sample frequency and also on the kind of parameters to be included in the report.

General indications of power to be measured (output electrical power), type of transducers are also provided and it is recommended to record also an independent measure of the energy drawn from or delivered to the grid for benchmarking.

Here as well are given indications on how to report information in deliverables and even sample record tables are shown as example.

4.2.2 Tidal energy conversion performance assessment

EMEC commissioned to ABP Marine Environmental Research also a standard for performance assessment of Tidal Energy Conversion Systems (TECs). The latest version ([3]) provides a means for measuring and auditing the power performance of single TECs of any type of technology. It is intended to be applied to the prediction of the absolute power performance of a given device and to the assessment of the differences in performance between various configurations of TECs and is structured in a similar way to the WEC case:

-Test Conditions: It is recommended to perform a bathymetric survey of the test site and an analysis of the seasonal migration of currents. Guidelines on the position of recording devices is given (10 minutes is the maximum resolution time suggested). A harmonic analysis is recommended to define a minimum of 20 current velocity constituents.

-Test Equipment: The net electric power should be measured by a power measurement device (transducer). Specification for tidal recording device accuracy and recommended errors are given.

-Measurement Procedures for TECs Device Performance: The minimum measurement period necessary for definition of the performance shall not be less than 15 days. Selected data sets shall be based upon 10-minute periods derived from the contiguous measured data.

-Derived Results: Power available is calculated from the kinetic energy active across the power capture area calculated through a time series of the measured current speeds. The power curve constitutes a plot of the power production record against the incident current resource and is to be derived applying the method of bins to the current velocity data. Proof of the convergence of the power curve should be given through the cumulative representation of power curve calculated along every day. Another parameter to be estimated will be the power coefficient. The expected Annual Energy Production (AEP) shall be obtained by combining the power curve with a frequency distribution of velocity for the site.

-Reporting Format: This is a brief description of the expected report format, including a general scheme of each section, a list of the figures to be included and the kind of information required.

In the DTI Tidal Current Energy Device Performance Protocol ([4]), two separate procedures are specified, both including field-based measurement program, data analysis methodology and standardised reporting format: one aims to define a methodology for resource characterization and the other one specifies a methodology for characterising the device performance:

-Procedure to characterise the local resource: Tidal currents can be reliably predicted based upon harmonic analysis. A 30-days continuous record prior to device deployment is acceptable for meeting the requirements of the MRDF scheme. It is suggested to measure the current resource using an Acoustic Doppler (AD) device. Recommendations on the maximum errors and on the positioning of the device are given. The data should have a 10-minute resolution and recognized harmonic analysis methods should provide harmonic constituents.

-Procedure to characterise the TEC device performance envelope: The main output of the device performance analysis should be a power curve produced using measured in-situ data and an assessment of the annual energy produced by the facility. Again, an AD device is used for the incident resource measurement. Information on the suggested placement of this unit is given (two options: one on the device or two up- and downstream). The measurement of the power is based on the approach suggested by corresponding standards in wind turbines and is generally measured using a power transducer based on values of current and voltage on each phase. Use is made even in this case of the concept of power curve, represented by a plot of the power production (y-axis) against the incident current resource record (x-axis).

4.2.3 Demonstration schemes.

Within the frame of the MRDF program, the DTI also issued two documents ([5] and [6]) defining a demonstration scheme and describing the actions to be taken in order to apply to the MRDF initiative. The first part introduces the scope of this policy, focusing on the need of additional funding for the marine renewable sector to bridge the gap to a commercially viable stage. This document defines then a series of requirements to be satisfied in order to reach the approval for the funding and a list of the eligible costs and projects. Importance is given to innovative projects with significantly different technology. To be eligible for an award any device should have been demonstrated to have performed continuously for three months at sea validating design, performance and cost of the project.

4.3 DEVICE DESIGN AND SELECTION OF THE COMPONENTS.

Table 9 Existing guidelines and protocols on device design and selection of components

Author/Institution	Title	Year	Content
DNV	Guidelines on design and operation of wave energy converters	2005	Detailed section on design process and evaluation techniques. Recommendations on material selection, fatigue analysis and general hydraulic, electrical and mechanical components. Information based on existing standards
Germanischer Lloyd	Guideline for the Certification of Ocean Energy Converters. Part 1: Ocean Current Turbines (draft)	2005	General document on design procedures and assessment. Recommendations are given on material selection, structural verification and loads calculation. Extensive reference is made to Offshore Wind standards.
EMEC	Draft Standard on basis of design of marine energy converters	2008	Schematic approach with specific recommendations and reference to existing standards
EMEC	A (draft) standard for – The Grid Interface of Marine Electrical Generators Installation	2008	Guidelines for interfacing marine energy device with electricity networks. Reference primarily made to British standards and wind experience
DNV	DNV OS-E301: Position Mooring	2004	Guidelines on mooring design aimed at general offshore structures. Does not take into account specificity of marine energy devices

The deployment of a prototype in real sea requires the definition of several technical and engineering details.

In this phase, the design of the structure and the selection of the material have to be carefully analysed considering reliability and economic requirements.

Moreover, several additional components, such as PTO equipment or foundations, have to be defined and their influence on the device performance needs to be taken into account while power connection to the grid requires the definition of electrical cables, instrumentation and control systems.

Due to the similar environment, marine energy technologies share many common requirements with offshore industry and for this reason many recommendations and standard defined in this field could be successfully applied to marine energy technologies after suitable modifications to reflect the difference in the consequence of failure and the ongoing “profit”. However, as said before, networks aimed at standardization and certification of marine energy converters have been created recently and it is likely that in future years an internationally recognized standard for design and operation of marine energy converters will be defined.

Survivability of the devices must play a particularly important role. On one hand, the existing offshore standards may be a safe approach in the initial technology phase, where this issue is of absolute priority. On the other hand, there are two arguments that justify a considerable review of any existing standard when applying to the marine energy sector: (i) Meeting the requirements of offshore standards might often bring along prohibitive costs and sometimes not be necessary, as both the loss of life and the environmental risk should be much lower. (ii) Due to their operation principle, certain devices tend to resonate and therefore “seek” naturally the most challenging situation regarding fatigue, mooring and sea-keeping. Further, the fact of separate body parts in relative motion to each other might expose the devices, typically surface-floating, to extreme loads from e.g. breaking waves. In some cases, common principles of wave-structure-interaction or other assumptions for ships or platforms might not simply apply to wave energy devices, but have to be carefully reconsidered. Among other WaveNET ([7]) items, a review of theoretical, experimental and field work for different wave energy devices with particular focus on survivability issues was done (B4 - Loads and Survivability—Wave and current load design criteria based on measured data at existing power plants and other coastal structures).

4.3.1 Design process.

One important protocol, commissioned by the Carbon Trust and carried out by DNV in 2005, defined a guideline for wave energy converters ([8]). Indeed, due to the similar deployment conditions, much of the content of this document could be easily applied also to tidal energy converters.

The objective of this Guideline is to provide interpretation and guidance on the application of existing codes and standards (mainly from industries such as Offshore and Maritime) to wave energy conversion (WEC) devices and should be read in conjunction with the Standards, Recommended Practices and other documents referred to in the text. The standards referenced generally guide the user to choose the relevant safety level. Thus they can be used for critical and less critical applications as far as they are relevant for wave energy devices. This document provides guidance on concept development, design, construction and life cycle processes to contribute to the reliability of the wave devices throughout their in-service life.

All the standards referred to are widely used by industry. A list of the relevant DNV Offshore Standards (OSs) and Recommended Practices (RPs) referred to is given in the references. The document covers different technical requirements and is particularly directed to certification and qualification procedures. Qualification may be defined as "the process of providing the evidence that the technology will function reliably within specific limits" and can be structured in a systematic approach easily applicable to new or existing technologies.

Within the Guideline evaluation techniques and approaches are presented. One interesting example is Value Management, a management tool used to ensure that value objectives are met through the application of various value management methods. Value management can be applied to products, business models, organisations, etc. For example, when selecting an alternative energy solution, many different economic factors will be considered to justify a certain development. Once a particular product or concept is selected, there are many ways to evaluate the design, manufacturing, operation and maintenance of the equipment to meet the value objectives. Typical techniques include Value Engineering and Life Cycle Analysis.

Other important suggestions concern the selection of materials like steel, concrete and composites and safety coefficients for design calculations. Load coefficients for mooring system analysis and methods for the foundation design are presented, although reference is made to DNV standards for offshore structures.

A section on the electric and mechanical equipment gives a brief outline and description of the whole set of components that may be included in the energy conversion chain with constant reference to international standards. Appendixes give also a technical insight of specific issues such as fatigue analysis methods and considerations on air-turbines and gearboxes.

Within its standard project, EMEC has also recently published a preliminary draft standard on design of marine energy converters ([9]).

This document provides a general step by step guidance for design of marine energy converters. A first distinction is made between the proper converter components (e.g. generator, gearbox, hydraulics etc.) and the structural ones (foundation or moorings, housing, case etc.). It is useful to list some of the recommendations outlined in each section:

- Operational conditions: Failure Mode and Effect Analysis (FMEA) is very important, description of device and of all the principal issues (working principle, equipment, models and methodologies for maintenance and decommissioning), definition of the design life
- Environmental loads: Important for the estimation of the loads, necessary bathymetry and/or coastal topography information (see environment specification references) with analysis of its influence on device performance, estimation of wind loads (API spectra formulation is suggested but other might be accepted), estimation of currents and waves, definition of design loads and conditions (it also gives a table of requested probabilities of occurrence for the kind of load to be considered)
- Loading considerations: A brief list of general non-environmental loads to be considered (static ones given by weight, variable due to the presence of personnel, accidental due to collisions or failures), the annual probability of a substantial failure should not be more than 0.001%, a table of suggested safety factors for the design of components is given.
- Fatigue Design considerations: Minimum design fatigue life is 20 years, a table of the fatigue loading estimation methods and their applicability is given in tab.2
- Harmonic Response: Natural frequency response might be required for some devices but it should be avoided in other cases, such as tidal devices
- Materials: concrete, structural steel (with corrosion protection), bronze, stainless steel, composites (carbon fibre might accelerate corrosion of adjacent metals in sea water)
- Corrosion Protection: general recommendations, given values for annual corrosion rates of the steel, corrosion factors should be taken into account also for moorings
- Floating Structures: the safety requirements for these devices are less strict than for the case of ships or offshore structures because they should work almost always un-manned.
- Marine Renewable Energy Converter (Electrical and Mechanical Design): reference to standard equipment for which several international normatives can be found, need for emergency safety systems, recommendations for normatives for liquids or gases kept in pressure, also recommendations for pipes in flexible or rigid material
- Instrumentation and Control Systems: importance of the safety monitoring and the fail-safe design, FMEA analysis is required.
- Cable Connections to Shore: they should be standard technology with proven years of satisfactory service

Deployment, retrieval, maintenance operations and decommissioning could also influence the choices in the design process, particularly if it is considered that the cost of the device might be strongly affected by these factors.

In 2005 Germanischer Lloyd has produced a draft document on certification of ocean current turbines ([10]), mainly based on previous existing recommendations for the Offshore Wind sector defined by the same GH. It distinguishes between different steps in the design assessment (A-, B- and C-design assessment) depending on the current state of the technology (whether it is at a prototype stage for test operation or already at a commercial phase) and it allows therefore different types of certification with different validities based on this distinction. The document covers extensively principles and methods for design and construction but it remains quite general and does not give specific indications on relevant parameters (such as, for example, safety coefficients). Remaining sections on performance, electrical and mechanical components make reference to other guidelines defined for offshore wind turbines and lack a critical analysis of the specificity involved in considering current turbines.

4.3.2 Grid Connection.

Grid connection is an important aspect in the design of the device and could have a significant impact on the cost and the maintenance requirements.

Recommendations for this issue are also found in the references previously cited.

DNV Guideline ([8]) points out that dynamic umbilical connections from the wave device to the seabed will be exposed to environmental loading due to currents and direct wave loading as well as forced motions of the floating wave device and that the static and dynamic response characteristic of the umbilical is similar to other compliant slender structures applied in the offshore in industry (e.g. flexible risers, hoses and control umbilicals). Such structures may have a pronounced nonlinear global response characteristic. It should be expected that possible non-linearities are strongly system and excitation dependent. Marine environment and underwater connections shall preferably be commercial off-the-shelf type approved products with known quality, reliability and performance.

The EMEC has produced a draft standard ([11]) specifically for this theme.

This document defines some requirements to be fulfilled. These requirements take the form of a number of output electrical parameters that must be taken into account during the overall design phase of the generation installation. These electrical parameters are established by the Network Operator and usually depend on network structure/topology, power capacity, Interface Point and any other issue the operator may consider relevant. Because of their unsteady and variable behaviour renewable energy installations may be given additional constraints whose severity may be expected to depend on their level of penetration into the given grid. When a small set of generation units is connected to the network, the connection scheme is usually regarded as distributed generation: power is supplied along the branches that link the network main nodes (large power plants) to the loads. On this topic a lot of work has been done for wind energy systems and it may prove useful for marine energy. With large farms things change substantially, as the Operator may request the plant to contribute to grid stability. On what concerns complementary issues such as protection and safe operation of electrical equipment at sea, general standards apply.

The document provides some guidelines for the interfacing of marine generation installations with a host electricity network but it has limited applicability to a connection voltage point below 132kV and to Great Britain.

The following topics are analysed:

- Electrical parameters:
  - Frequency: standard and exceptional operation conditions; reference value is 50Hz;
  - Voltage range and control for both enduring requirement and occasional service;
  - Power Factor control; unity PF is usually requested. Variable speed generators achieve the requirement via a power converter while constant speed machines mostly rely on capacitor banks connected in parallel.
  - Power quality:
    - Harmonics emissions: although voltage harmonic distortion has been a non negligible source of concern in the past, nowadays it represents a minor issue. Constant speed generators design should ensure sinusoidal voltage waveforms, this may imply some low-pass filter connected in parallel; modern variable speed drives equipped with IGBT power converters hardly inject any relevant harmonic into the grid;
    - Voltage unbalance;
    - Flicker or voltage fluctuations: depending on the strength of the grid connection, the resulting power fluctuations can result in grid voltage fluctuation which, in turn, can cause a wide range of undesired annoyances such as bulb brightness flickering. The existing grid harmonics at the Interface Point must be taken into account. The issue is of major concern, especially for wave energy generation installations: without short-term energy storage units, power fluctuations may be unacceptable in weaker grids.

- Protection; guidelines may be outlined as follows:
    - Protect the marine generators form electrical faults and overloads within the device and from the effect of disturbances caused by the electrical infrastructure of the network;
    - Protect the electrical infrastructure from internal faults

  At this stage of development, marine generation installation are not expected to contribute to grid stability, hence marine generators are quickly disconnected in case of grid fault. Circuit breakers represent the most attractive option, passive protection systems such as fuses instead are not encouraged since they need to be replaced after use and off-shore units may be difficult to access for maintenance.

- Earthing: follow standard procedures for both on-shore and off-shore infrastructure
- Electrical islanding: may be done applying the appropriate standards.

- Electromagnetic compatibility: may rely on a document produced by the wind turbine industry.
- Commissioning and Information: prescribed tests must be performed before commencement of operation. All information and data concerning the installed electrical equipment must be handed over to the Network Operator.

It is suggested that pre-design of the generation installation may be done referring to documents and standards developed by the wind energy and/or marine offshore industry together with acknowledged standards and regulations for general electrical installations. The ultimate design must be discussed with the Network Operator.

4.3.3 Moorings and Foundations.

The design of moorings and foundations is strictly dependent on the kind of device considered. Most of the tidal devices currently being developed are fixed structures installed at limited depths while a large part of wave energy devices are floating structures that require a slack mooring system.

In the DNV Guideline ([8]) and EMEC Design standard ([9]) it is suggested to make reference to existing standards for offshore structures, such as DNV standard OS-E301 ([12]) which indeed constitutes a certified procedure for mooring design.

In the case of marine energy converters and particularly floating wave energy devices, however, there is still uncertainty on the influence of mooring equipment on the performance of the device and ongoing research work is being concentrated on this issue.

A review of possible design configurations was given by Johanning, Smith and Wolfram ([13]). In this paper, mooring system configurations and components from the offshore industry suitable for WEC units are identified. Possible mooring configurations for WECs are discussed and it is argued that not only station keeping but also the overall performance characteristics of the WEC mooring should be considered in the design. Work on mooring design for wave energy converters and its influence on performance has also been carried out by Fitzgerald ([14]).

Shoreline installed devices generally have concrete foundations and support structure, and most use oscillating water columns, breakwater- OWCs or overtopping devices as the operating principle. Devices installed at nearshore will mostly be gravity anchored, resting directly on the seabed, or fixed to the seabed. Common energy extraction methods for nearshore devices are OWCs and OTDs, but wave activated bodies are also used. Whilst the techniques to anchor shoreline and some nearshore devices could follow established engineering procedures, each offshore device requires an independent design study to ascertain the extreme environmental loads that must be withstood, cost effectively. The moorings for offshore devices are more complex and interact strongly with the energy extraction method and the orientation of the device to the mean wave direction, for efficient power conversion.

The paper outlines then the different concepts generally used in moorings such as spread moorings (catenary) or single-point ones. The suitability of each method to wave energy conversion is briefly considered and some additional analysis of the costs and selection of the equipment is given.

No information is provided on tidal devices. It can be suggested that many of the results given before can be successfully applied to these devices, especially when to be held fixed with respect to the seabed. The case of floating tidal systems is different since they may have different requirements from the wave energy ones.

4.4 MANUFACTURING, RELIABILITY AND MAINTENANCE

Table 10 Existing guidelines and protocols on manufacturing, reliability and maintenance

Author/Institution	Title	Year	Content
DNV	Guidelines on design and operation of wave energy converters	2005	Assumes requirements for fabrication and testing in line with the same for offshore installations. Describes failure analysis techniques and identifies possible risks
Andrew McNicoll, Neptune Ross Deeptech (EMEC)	Guidance notes for marine renewable energy systems, manufacturing assembly and testing	2008	Guidance notes on general aspects of manufacturing and assembly mainly useful for project definition and supervision. Rather general and based on existing normative
BMT Cordah for EMEC	Draft Standard on Reliability, Maintainability and Survivability for Marine Energy Converters	2008	Defines reliability and survivability requirements identifying strategies and covering all the stages of development. Very general and based on existing standards. Does not take into account device specificity

4.4.1 Manufacturing and assembly

Manufacturing processes are an important issue to be taken into account when the feasibility and economic profitability of the converter has to be assessed.

According to the DNV Guideline ([7]), the requirements for fabrication and testing are, in general, in line with the requirements for offshore installations. However, special considerations should be implemented considering the access to structure and equipment during the in-service life, the planned maintenance regime and required reliability of the device. The particular expertise required of manufacturers of WEC devices will vary according to the make-up of the device and power take-off system employed. However, suitable manufacturers will be able to demonstrate and incorporate similar experience and track record to enable successful manufacture of the WEC device.

A study commissioned by EMEC has resulted in a draft document illustrating guidance notes for manufacturing, assembly and testing ([15]).

The design requirements of a marine energy system exhibit particular needs due to the harsh operating environment in which they are intended to be operated. Therefore the document purpose is to address the project developer to the proper choices on what concerns a number of issues regarding manufacturing, assembly and test procedures:

- Contract review
- Manufacture and workmanship
- Welding
- Inspection and testing of welds
- Assembly
- Electrical installation
- Surface coating
- Factory & Acceptance Testing
- Certification

Though it is unlikely that the amount of information contained in the document is enough to give a full picture of the whole process, the guidelines it presents may be sufficient to enable the project leader to supervise every process stage and to take an active role in the dialogue with the companies endorsed with the tasks. From the document one may also retrieve useful information to correct or improve the device design. In the appendix some example report sheets are presented. The normative the document refers to is quite exhaustive.

4.4.2 Maintenance and Reliability.

A crucial aspect to be addressed for the development of marine energy technologies is the assessment of the reliability and survivability of the device and its components.

The DNV Guideline ([7]) provides a good analysis of the available approaches for failure mode identification and risk ranking. A commonly used technique to carry out such a study for new technology is the What-If technique. A cited example is the SWIFT (Structured What-If checklist Technique) method. Other techniques are FMECA (Failure Mode, Effects, and Criticality Analysis) and FTA (Failure Tree Analysis) and may also be applied depending on the project stage.

A typical offshore development risk assessment would include the follow category of events (consideration should be given to all phases during the device’s life: fabrication, installation, in-service and decommissioning):

- Anchor/foundation failure
- Mooring failure
- Breach of water integrity of compartments or equipment
- Stability failure
- Collision risks
- Interference with commercial and recreational marine activities
- Structural failure
- Fishing gear impact
- Personnel risks to operators and to the general public
- Pressure containment failure from hydraulic or pneumatic systems
- Electrical failures and shore connector failures
- Seismic events
- Fires
- Interference floating debris with device

By analysing the above failures coupled with the engineering limits of the device, the consequences can be predicted. The frequency of failure can be evaluated through the use of reasonable estimates and historical failure data.

A draft standard on reliability issues ([16]) has also been commissioned by the EMEC.

This standard focuses on three areas that are of fundamental importance to success and should be considered at all stages from concept to production. These are:

- Reliability, and in particular the trade-offs between component reliability and system redundancy to achieve the required availability
- Maintainability, and in particular the methods of, and access for, preventive and corrective maintenance
- Survivability, and in particular the opportunities for avoiding extreme loadings and conditions

Once main factors affecting RMS are individuated, the document outlines the procedures that may enable:

- The set-up of a strategy that leads to correct design concept
- To reduce the risk (risk assessment)
- To define RMS targets that if met lead to a viable energy farm
- The definition of appropriate design approaches
- Evaluate assurance: predictions against targets

Furthermore, the draft presents some method and/or potential tools

- to achieve significant improvements (from feedback and through change)
- to reduce risk (through testing and managing)
- example analysis worksheets
- example of risk assessment procedure

The guidelines cover all stages of development: conceptual, prototype, pre-commercial and farm stage. According to authors, it addresses:

- marine energy converter developers to demonstrate and improve their converters
- project developers to evaluate their projects
- investors to do due diligence on their decisions

A crucial point yet to be defined within marine energy ([17]) is the definition of appropriate failure rates for components, particularly if using (i) non-marine components or (ii) marine components from other industries. In certain cases the failure rates of certain components (say from the OREDA data base) might not reflect the way they operate in a wave energy device (duty cycle for example).

4.5 SAFETY REQUIREMENTS

Table 11 Existing guidelines and protocols on safety requirements

Author/Institution	Title	Year	Content
DNV	Guidelines on design and operation of wave energy converters	2005	Outlines expected safety targets for marine energy converters. Requirements are less restrictive than offshore technologies being these devices unmanned structures

As normally unmanned structures, the safety levels of WEC devices must be balanced by consideration of the need of the device to survive extreme conditions, the protection required while personnel are on board, and the protection of third parties. Survival requirements could be directed to protect reputation at a certain phase of the device development and/or to protect the investment made in the asset. However, it is also important to define the safety level considering any possible impact on fatigue aspects (in most cases the likely governing factor in the design) and other deterioration mechanisms.

The DNV Guideline ([7]) addresses several aspects related to safety issues. According to this reference, in defining targets for the qualification process or preparing the design basis, an overall safety philosophy should be clearly established covering all phases from conceptual studies up to and including decommissioning.

Moreover, fire protection should be considered for protection of personnel during maintenance and inspection activities and protection of the device during in-service and maintenance. The evaluation of fire protection system requirements should be carried out during the risk assessment. Due consideration should be given to health and safety requirements. Temporary portable fire detection, portable extinguishers and ventilation facilities should be installed prior to undertaking maintenance work within the device.

A risk assessment analysis should also include stability and watertight integrity among the relevant factors for safety.

4.6 REFERENCES.

[1] EMEC – *Performance Assessment for wave energy conversion systems in open-sea test facilities*– 2005, available at http://www.emec.org.uk/pdf/EMEC_Performance_Assessment.pdf .

[2] Smith G. and Taylor J., Heriot-Watt University and University of Edinburgh for DTI – *Preliminary Wave Energy Device Performance Protocol.* – 2007, available at*:* http://www.berr.gov.uk/files/file38989.pdf

[3] Swift R.H., ABPMer for EMEC –*Performance Assessment for Tidal Energy Conversion systems (TECS) in Open Sea Test Facilities* – 2008, available at: http://www.emec.org.uk/pdf/standards/Tidal%20Performance%20Standard%20-%20Draft%205.pdf

[4] University of Edinburgh for DTI –*Preliminary Tidal Current Energy: Device Performance Protocol*– 2007, available at: http://www.berr.gov.uk/files/file38991.pdf

[5] DTI –*Wave and Tidal-stream Energy Demonstration Scheme – Definition document*– 2005, available at: http://www.berr.gov.uk/files/file23963.pdf

[6] DTI –*Wave and Tidal-stream Energy Demonstration Scheme - guidance notes for applicants*– 2007, available at: http://www.berr.gov.uk/files/file39879.pdf

[7] VV.AA. – *WaveNet: Full report* – 2003, available at: www.wave-energy.net/Library/WaveNet%20Full%20Report(11.1).pdf

[8] DNV for Carbon Trust – *Guidelines on design and operation of wave energy converters* – 2005, available at: http://www.dnv.no/Binaries/WECguideline_tcm28-181675.pdf

[9] EMEC – *Draft Standard on basis of design of marine energy converters* – (2008), available at
http://www.emec.org.uk/pdf/standards/Basis%20of%20Design%20-%20First%20draft.pdf

[10] Germanischer Lloyd – *Guideline for the Certification of Ocean Energy Converters, Part 1: Ocean Current Turbines (draft)* – 2005, available at: http://www.gl-group.com/en/ren/6454.php

[11] EMEC – *A (draft) standard for – The Grid Interface of Marine Electrical Generators Installation.* – available at: http://www.emec.org.uk/pdf/standards/Grid%20Interface%20Standard%20-%20Draft%202.pdf

[12] DNV – *DNV-OS-E301, Position Mooring* – 2004, available at: http://webshop.dnv.com/global/category.asp?c0=2624#2610

[13] Johanning L, Smith G H, Wolfram J - *Mooring design approach for Marine Energy Converter* – 2006, Proc. IMechE. Part M: J. Engineering for the Maritime Environment (special edition for Marine Renewable Energy) Volume 220, Number 4, pp. 159-174

[14] Fitzgerald J. - *Proposal for safe moorings design approaches* – 2007, Wavetrain Deliverable nº 17

[15] Andrew McNicoll, Neptune Ross Deeptech for EMEC– *Guidance notes for marine renewable energy systems, manufacturing assembly and testing* – available at*:* http://www.emec.org.uk/pdf/standards/MFT%20Draft%201.pdf

[16] BMT Cordah for EMEC –*Draft Standard on Reliability, Maintainability and Survivability for Marine Energy Converters* – available at: http://www.emec.org.uk/pdf/standards/RMS%20Standard%20-%20Draft%203.pdf

[17] Wolfram J. - *On assessing the reliability and availability of marine energy converters: the problems of a new technology* – 2006, Proc. IMechE Vol. 220 Part O: J. Risk and Reliability

5. POLICY ISSUES AND ENVIRONMENTAL IMPACT ASSESSMENT

5.1 INTRODUCTION

The deployment and operation of marine energy converters requires the allocation of a marine area, generally under state jurisdiction, and might sensitively affect the physical environment and subsequently human and biological activities in the surrounding zone.

It is therefore clear that no installation is legally possible without the preliminary authorization by the public bodies in charge. This consent is usually given on the basis of a detailed analysis of the environmental and social impact of the technology to be installed.

At present, there is not yet any European common procedure for the permitting of marine energy converters deployment and no standardised approach has been established to perform an environmental impact assessment. Uncertainty still exists regarding influence and impact of developments on the environment. Projects that are undergoing full-scale demonstration have been proposing specifically defined criteria to meet the requirements for authorisation.

5.2 POLICY AND PERMITTING PROCEDURES

Table 12 Existing guidelines and protocols on policy and permitting procedures

Author/Institution	Title	Year	Content
EU	Directive on Environmental Impact Assessment	2003	Requirement of an environmental impact assessment before building permission. Does not mention specifically marine energy technologies
IEA-OES	Review and Analysis of Ocean Energy Systems Development and Supporting Policies	2006	General resume of supporting activities for marine energy that includes also funding of R&D and device deployment
Scottish Government	(SEA) Strategic Environment Assessment for Wave and Tidal Energy	2007	Assessment of the Environmental Impacts of the Scottish Wave and Tidal Energy Plan
Ram B. et al. (EPRI)	EPRI DOE NREL – 008 US, Wave Power in the US: Permitting and Jurisdictional Issues	2004	Selection of US federal regulations addressing environmental impact requirements of marine installations

Environmental legislation requirements for marine energy farms are uncertain in many countries at this moment. According to the European Union (EU) Directive on Environmental Impact Assessment (EIA) (Directive 85/337/CE), all EU member states must commission an assessment of the environmental consequences of certain types of projects, including power stations, before building permission is granted. Another European legislation amending or complementing this directive has appeared (Directive 97/11/EC, Directive 2003/35/EC) and has been adopted in the national legislation of Member States.

However this directive does not specifically include marine energy farms in its annexes owing to the current status of this technology. Nonetheless it is reasonable to suppose that it will be contemplated in a near future; like offshore wind energy. Therefore, it can be expected that EIA based on EC directives will become an essential element for permitting large-scale ocean energy schemes. Meanwhile developers have to be oriented along national laws where possible, but as mentioned before, legal frameworks are still under construction and vary between countries. UK legislation is, for instance, more severe than in Portugal, the former requires a full EIA for wave energy test facilities while in the latter, a less demanding document (Incidence Environmental Study) is enough. Another example of the differences is that the expenses for deploying wave energy devices are much higher in Denmark than in the UK. These are all shown in the article about the Waveplam project presented in the last ICOE conference in Brest ([1]).

Consent processes have been documented for some specific projects. Two examples are represented by the Wave Hub ([2]) and the European Marine Energy Centre (EMEC [3]), the first built test sites for wave and tidal energy devices, and both located in the UK. The same is expected to happen with other planned test infrastructures, like the Portuguese Pilot Zone or the bimep, in the Basque Country.

As a result of the Coordinated Action on Ocean Energy (CA-OE), a deliverable on what is called non technological barriers was released, addressing environmental, economic, policy and promotion aspects of ocean energies ([4]).

The process is nevertheless more complex for individual developers deploying their devices, like in the case of Wave Dragon, a Danish developer, installed in Wales ([5]).

A report issued in 2006 ([6]) by the International Energy Association – Implementing Agreement on Ocean Energy Systems (IEA-OES) briefly reviews the types of policy which support and influence the development of ocean energy technology. Common policies that support many of the technologies analysed are assessed, including their impact on government renewable and ocean energy R&D budgets. Market deployment support mechanisms are explored and the key policies in individual countries are identified and described. Important consenting and environmental activities are also described.

A review of permitting and jurisdictional issues related to wave power deployment in the USA has been prepared by the Electric Power Research Institute (EPRI) in 2005 ([7]). The document includes a selection of relevant federal regulations addressing potential environmental impact at the project site.

The WAVEPLAM ([8]) is an international European project, whose purpose is to develop tools, establish methods and standards, and create conditions to speed up introduction of ocean energy onto the European renewable energy market and is likely to tackle this issue giving a good overview of the policy and permitting procedures in Member States including best practices.

5.3 ENVIRONMENTAL IMPACT ASSESSMENT

Table 13 Existing guidelines and protocols for environmental impact assessment

Author/Institution	Title	Year	Content
EMEC	Environmental Impact Assessment (EIA) Guidelines for Developers at the European Marine Energy Centre	2005	General guidelines for environmental impact assessment. Part of a standard definition program likely to produce recognized protocols

One of the most important issues identified in relation to WEC developments is the necessity of these devices to be subject to an Environmental Impact Assessment (EIA). Even though, as said before, this is not strictly necessary in every country, concern exists about the environment, and the need rises to develop standards that allow assessing and comparing impacts.

Halcrouw Group was responsible for the publication of the Environmental Statement of Wave Hub ([9]), an extensive document that aimed to accomplish and assess all the potential impacts of deploying wave energy devices and operating them.

An EIA strategy has been defined also for the wave energy Portuguese Pilot Zone ([10]) that focuses also on the importance of public awareness to limit negative impact perception by the population.

Other recent marine energy projects had to provide environmental impact specifications to obtain consents. This was the case for the Wave Dragon ([11]) whose Environmental Impact Assessment process has included detailed investigation of the chosen site (the county of Pembrokeshire in Wales).

EMEC has raised awareness for this issue and written their own guidelines for developers to take into account when planning to deploy a WEC or array of WECs ([2]) and has already made efforts to facilitate and coordinate the development of environmental standards for the marine energy sector. To date, two workshops have been performed under EMEC coordination, both with representation from the EquiMar project.

The project for EMEC standards in environmental issues has been temporarily closed in September 2008, and is waiting for possible future funding. The EMEC project aims at bringing experts in the field together and launching standards.

As output of the second workshop some topics for future guidelines to environmental standards have been identified as listed below:

- Navigation/shipping interference
- Submarine/MOD interference
- Marine Archaeology
- Fisheries exclusion
- Landscape and visual impact
- Electromagnetic interference
- Underwater vibration
- Wildlife collision
- Wildlife entanglement and entrapment
- Barrier effect (fish cetaceans)
- Marine wildlife behavioural changes (underwater noise)-construction
- Marine wildlife behavioural changes (underwater noise)-operation
- Seabed damage/disturbance
- Energy extraction
- Sediment movement

Marine energy deployments need an area where navigation is avoided. This will involve in many cases new spatial planning by the competent local authorities nearby the marine energy farms. A guidance on Navigational safety issues has been written by the Maritime and Coastguard Agency ([12]), which provides a list of matters that should be determined, including site position, safety zones, navigation, communication, search and rescue.

Fishing activity will be affected by the presence of wave and tidal energy devices. Firstly, because of the restriction of use of the area; installations of marine energy converters will require an area on the sea where navigation is normally prohibited, so spatial planning will be necessary to arrange new forms of use of the marine area. The British Wind Energy Association in cooperation with the local fishing Associations have written a document with recommendations on how to deal with this issue from the start, the kind of agreements that should be made and the best way of acting in any situation.

Another impact of the installations is the effect these may have on fish. On one hand, reducing fishing pressure could increase the number of individuals in the area, resulting in a beneficial effect for fish stocks in the long term. On the other hand, noise and vibration could make the fish species move away from the site.

Regarding visual impact on seascape, the target seems to be the assessment of the seascape character. There are also guidelines about this topic, from the wind energy industry. Among the papers delivered on the subject by the Scottish Natural Heritage, and the Countryside Council for Wales is the Seascape Character Assessment ([13]).

To avoid seabed damage while carrying out baselines studies to determine the environmental impacts, several bodies have published best practice guides.

The Joint Nature Conservation Committee produced guidance on baseline survey requirements while EMEC have developed ROV guidance.

Many authors point at noise produced while installation and decommissioning of WECs, as well as during the normal operation of the devices themselves, as a great element of disturbance upon various groups of animals such as birds, marine mammals and fishes.

Andrew B. Gill, from the Cranfield University, published an article ([14]) in the Journal of Applied Ecology, dealing with the ecological implications of offshore renewable energy developments. His concern is the effect on coastal ecology by noise, EM (electromagnetic) fields or physical disturbance of the seabed by piling and drilling, and he concluded that the extent of the impact would be proportional to the extent of the disturbance factor and the resilience and stability of the target community. In this article, he pointed out that the impacts would act on an already degraded environment, since coastal areas are mostly affected by human activities since long time ago.

COWRIE wrote a whole guidance document ([15]) about this, focusing on the importance of being aware of cumulative impacts on coastal ecosystems from previous human activities that might have been affecting the coast long before the renewable energy developments are planned.

5.4 LIFE CYCLE ANALYSIS

A very common tool for assessing the environmental impact of any product is the Life Cycle Analysis, which characterises the environmental footprint of a good by carrying out a cradle to grave study. It focuses on the total energy use and the CO2 emitted in the production of the product throughout its development. There are various device developers that have published their Life Cycle Analysis, namely Wave Dragon ([16]), Seagen ([17]) and Pelamis ([18]).

5.5 LIST OF REFERENCES

[1] **C. Huertas-Olivares, H. C. Soerensen, N. Rousseau, J. L. Villate, J. R. López , A.Sarmento, I. Russell, F. Neumann -** *First outcome of the WAVEPLAM project: Assessment of Non technological barriers and Best practices* – 2008, Proceedings of the 2nd International Conference on Ocean Energy, Brest.

[2] **Bond Pearce** – *Wave Hub facility, Consents and Permitting considerations* – 2005, available at: http://download.southwestrda.org.uk/file.asp?File=/projects/general/Consents.pdf

[3] **EMEC** – *Environmental Impact Assessment (EIA) Guidelines for Developers at the European Marine Energy Centre* – 2005, available at: http://www.emec.org.uk/pdf/EMEC_EIA_Guidelines.pdf

[4] **Soerensen, H. C. & Russell, I**.- *Work Session 5 Environmental, Economics, Development Policy and Promotion of Opportunities* – 2008, CA-OE project no. 502701, SPOK, Copenhagen, March, 30 pp.

[5] Hansen, L.K., Soerensen, H. C. et. al. - *Experiences from the approval process for Wave Dragon* – 2003, 5th European Wave Energy Conference, Cork, Ireland, 8 pp.

[6] AEA Energy & Environment on the behalf of Sustainable Energy Ireland for the IEA's Implementing Agreement on Ocean Energy Systems – *Review and Analysis of Ocean Energy Systems Development and Supporting Policies* – 2006, available at: http://www.iea-oceans.org/_fich/6/Review_Policies_on_OES_2.pdf

[7] Ram B. et al.–*EPRI DOE NREL – 008 US, Wave Power in the US: Permitting and Jurisdictional Issues* – 2004, available at: http://oceanenergy.epri.com/attachments/wave/reports/008_Wave_Permitting_Issues_Final.pdf

[8] www.waveplam.eu

[9] Halcrow Group Limited - *Wave Hub Environmental Assessment* - , available at: http://download.southwestrda.org.uk/file.asp?File=/projects/general/Environmental%20Statement.pdf

[10] Huertas-Olivares C., Neumann F., Sarmento A. – *Environmental management recommendations for the wave energy Portugues Pilot Zone* – 2007, Proceedings of the 7th European Wave and Tidal Energy Conference, Porto.

[11] Russell I., Sorensen H.C. – *Wave Dragon: Results from UK EIA and Consenting Process* – 2007, Proceedings of the 7th European Wave and Tidal Energy Conference, Porto.

[12] Maritime and Coastguard Agency - *Marine Guidance Note 275: Proposed UK Offshore Renewable Energy Installations (OREI), Guidance on Navigational Safety Issues* – 2004, available at: http://www.mcga.gov.uk/c4mca/mgn275-2.pdf

[13] M. Hill, J. Briggs, P. Minto, D. Bagnall, K. Foley, A.Williams - *Guide to Best Practice in Seascape Assessment* **–** 2001, Countryside Council for Wales. Brady Shipman Martin University College Dublin).

[14] Andrew B. Gill - *Offshore renewable energy: Ecological implications of generating electricity in the coastal zone* **–** 2005, Journal of Applied Ecology 42

[15] Oxford Archaeology with George Lambrick Archaeology and Heritage for COWRIE Ltd. - *Guidance for Assessment of Cumulative Impacts on the Historic Environment from Offshore Renewable Energy* – 2008, available at: http://www.offshorewindfarms.co.uk/Assets/ccowrie_ciarch%20web.pdf

[16] Soerensen, H. C. & Russell, I. - *Life Cycle Assessment of the Wave Energy Converter: Wave Dragon* – 2006, International Conference on Ocean Energy Bremerhaven, 8 pp.

[17] C. A. Douglas, G. P. Harrison and J. P. Chick - *Life cycle assessment of the Seagen marine current turbine* -2008 **,** Proceedings of the Institution of Mechanical Engineers, Part M: Engineering for the Maritime Environment, 222 (M1).

[18] R.P.M. Parker, G.P. Harrison and J.P. Chick - *Energy and carbon audit of an offshore wave energy converter* -2007, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 221 (8), available at: . http://journals.pepublishing.com/content/830l26865123p760/?p=23a66932b90a44cf97cd9bf43bd32ce7&pi=4

6. ECONOMIC ASSESSMENT OF LARGE-SCALE DEPLOYMENT

6.1 INTRODUCTION

Electricity production from marine energy conversion is rapidly developing into an industry. Private and public bodies are putting research efforts in this area because it is believed that the global market has significant value and that the sector will soon become commercially viable. Although many technologies are presently being developed, only a small number of devices have generated electricity from the marine environment. From such a small experience base it is very difficult to reliably assess the economic feasibility of alternative technology options for large-scale electricity generation. With a few notable exceptions, much of the work on marine energy costing that has been published to-date concerns relatively small deployments (up to around 100MW rated capacity) and the economic implications of manufacturing, installing and operating a large-scale array have not been fully explored. Comparison between individual marine energy technologies is therefore not straightforward for potential investors or policy makers. Although several studies on device economics have been completed, an accepted standard approach for calculating the cost of electricity from large-scale marine energy projects has not been developed.

Two of the most widely referenced studies are reports by the UK Carbon Trust and US Electric Power Research Institute. In 2006 the Carbon Trust published the results of a detailed study, named Marine Energy Challenge, into the cost competitiveness and potential growth of wave and tidal stream energy ([1]) in which consultant engineers evaluated the feasibility of eight wave energy devices and five (TBC) tidal stream devices. In these reports the cost of energy from each device is estimated through the present value approach, wherein the cost of electricity is determined from estimates of power production, capital cost and operating cost and future costs are reduced to their present day equivalent by application of appropriate discount rates. Different scenarios (optimistic or pessimistic) were evaluated by considering upper and lower-bound cost estimates for individual device components. Component cost estimates were provided by engineering experts and may have varied between technologies. An indication of the future cost of electricity from marine technologies was obtained by applying learning curves and a brief discussion is given on the design processes which could lead to cost reduction. The costing methodology used by one of the engineering consultants on this project was also published [2]. The Electric Power Research Institute (EPRI) has also published two reports concerning economic assessment methodologies respectively for wave energy power devices ([3]) and tidal in-stream plants ([4]).

The EPRI studies focus on the North American (United States) market and legislation. Three standard methodologies, based on U.S. regulations, are proposed for:

1. utility generators (UG),
2. municipal generators (MG),
3. non-utility generators (NUG).

Example calculation sheets are given for a regulated utility generator (A) and a regulated municipal generator (B) in the Appendix to [3]. Key differences are in the obligations set by the Grid Operator since this determines its position on the market. Their proposed cost analysis takes the following factors into account:

- capital cost, calculated as the sum of the costs of the components
- income taxation
- incentives (they vary from state to state, some examples are reported).

A cost comparison with other energy alternatives is attempted.

6.2 PRESENT VALUE COST OF ELECTRICITY APPRAISAL

In general, the cost models that have been used to appraise individual marine energy generating technologies are based on the widely used Net Present Value approach in which future investments are discounted to their present equivalent, then all expenditure aggregated and divided by the net electrical output (models are described in [2] – [8] and others). Although similar in concept, the approaches used are not consistent in the cost components included or in the manner in which model factors such as discount rate or risk are considered. Such approaches are inherently dependent on preliminary concept design and on cost data available for individual components. Site- and device-specific uncertainties associated with accessibility and maintenance interventions may also strongly influence cost estimates. Comparison between different marine concepts is therefore not straightforward. In the following sections, four of the principal inputs to a present value cost model are reviewed.

6.2.1 Electrical Output

Predictions of the electrical output from a single wave device are discussed in the technical literature review of WP2-4. Cost models by the Carbon Trust and EPRI employ device power matrices and annual sea-state occurrence statistics to estimate annual electrical output from a device. In most cases, the device power matrices used were obtained from developers.

Variability of supply is also significant both with regard to the market penetration of marine systems and the value of the generated electricity. Boehme et al. [5] study the correlation between the electrical supply provided by large-scale deployment of Pelamis type devices in Scottish waters and the Scottish demand. Long term variability was also studied by Sinden [9].

6.2.2 *Discount, Risk and Uncertainty*

Several studies (e.g. [1], [5]) have shown that cost of electricity can vary by up to 30% due to variation of the discount rate over the range 8-15%. The discount rate used is related to the risk associated with the investment. One approach for accounting for risk is the Capital Asset Pricing Model (CAPM) which entails specification of the discount rate as a function of a risk parameter (typicallyβ) which is a measure of a cashflows correlation with the movement of financial markets. Most methodologies applied to marine energy costing discount all future cash flows using the same discount rate ([2], [3], [4], [6], [7]). Using a single discount rate for all cash flows including both fixed and variable operating costs and revenue due to electricity generation implies that all cash flows are equally risky. However, this is unlikely to be the case since, for example, long-term maintenance contracts could be secured. Boud and Thorpe ([6]) reviewed the risk coefficient (β) of the shares of 28 companies with relevance to the marine sector and suggested that a beta value of unity, and hence a discount rate of 10%, would be applicable to a wave energy project. Similarly they suggest that the cost of capital for a wave power project is expected to be approximately 10%.

In a series of papers, Awerbuch (e.g. [10]) argues that different risk parameter**s** should be applied to separate cash flows including fuel expenses, fixed maintenance contracts and variable maintenance costs. This method results in lower discount rates – hence higher present values - for cash flows that are correlated with the market (i.e. fuel prices and variable O&M) and high factors for those that are independent of the market (i.e. long term maintenance contracts). Whilst a risk-adjusted discount rate is applied to each cash flow, the future cost of electricity is discounted by the weighted average cost of capital (WACC)[1]. Unit electricity costs calculated by this approach represent the cost at which a 30 year generation contract would trade assuming an efficient market. Employing this methodology, it can be shown that traditional single-discount rate cost models significantly underestimate the cost of traditional fossil fuel generators whilst slightly overestimating the cost of capital intensive renewable energy projects.

It is relatively straightforward to consider the sensitivity of unit cost to the uncertainty associated with individual inputs. Upper- and lower- cost bounds are identified in several studies ([1], [7], [12]) and Monte Carlo simulations employed in others ([18]) to obtain a probable range of costs. The ranges used are not necessarily consistent between sources. Entec Ltd ([2]) attempt to rationalise the uncertainty associated with individual inputs by assigning error bounds based on qualitative assessment of the reliability of a variable estimate (i.e. variation of ±10, 20, 50% for high, medium and low confidence) assigned to each component cost or input. An alternative approach in which fuzzy logic and neural networks are employed to link the uncertainty of each input to the uncertainty of the predicted cost is outlined in a recent study by Cocodia [11] and demonstrated by application to Floating Offshore Structures.

6.2.3 *Capital Cost*

Several studies have been published concerning the cost of individual devices. Various studies are publicly available from the DTI ([7], [12], [13]) but commercially sensitive information (component costs) has generally been omitted.

A major consideration for all offshore renewable energy schemes (marine and offshore wind) is the cost associated with site-shore transmission and grid strengthening required. Several relevant studies of this cost have been completed on behalf of the Scottish Executive ([5]), as part of the development of the WaveHub project ([14]), as part of the EPRI reports, in various wind-farm studies ([15], [16] amongst many others) and, more recently in [17]. Since these costs will be similar irrespective of the generating technology deployed at the offshore site, transmission costs are not considered in detail within the EquiMar project.

6.2.4 *Operation & Maintenance*

Since few marine energy schemes have been deployed offshore reliable estimates of the operating cost for large-scale deployments are not available. Operating cost estimates for marine energy projects have typically assumed annual O&M costs as a fixed percentage of the initial investment cost (e.g. [2], [7]). More recently, parametric models have been developed – used in [6] to estimate WEC maintenance costs on the basis of the frequency of failure and repair time for various components. A similar approach is used in the site-specific studies supporting [3] and tidal stream device study of [18]. These parametric models do not appear to take account of the duration of wave conditions suitable for site-access. From a study of the Blyth offshore wind-farm, AMEC [19] found that whilst the actual duration of offshore operations can be planned with reasonable accuracy, the waiting on weather allowance was larger than planned and remains difficult to predict.

---

[1] Dependent on the investor but national rates may be obtained from e.g. www.erecusa.com

Although not directly comparable, it is informative to review the methodologies used by the wind industry to estimate operational and maintenance requirements whilst some activity cost and day-rate information is available from the oil and gas sector. Alternative methods for scheduling offshore wind farm maintenance are discussed in [20], [21] and others.

6.3 LONG TERM ECONOMICS

The studies outlined above concern methods used to estimate the capital cost, operating cost, performance and hence cost per unit of generated electricity from existing technologies. Policy makers and utilities are concerned with the relative market position of emerging technologies and so the prospects for future cost reduction are important. In the following, the prediction of future costs, the wider economic implications of large scale deployment and methods in which these diverse factors may be considered are reviewed.

6.3.1 Future Cost Estimation

Learning or experience curves are widely used to infer future costs. This approach is based on the assumption that costs will fall by an assumed percentage with each doubling of cumulative installed capacity. This covers all mechanisms which could force cost reduction. Various learning rates (typically between 10-20% of cost reduction per doubling of cumulative production ([1], [3]) have been proposed for the marine energy sector based on cost trends from other industries ([22], [23]). However, both the transfer of learning rates between industry sectors and the use of learning rates derived from early stage industries is cautioned ([22], [24]). Learning rates applicable to the marine industry are presently the subject of a UKERC study led by UEDIN ([25]).

6.3.2 Economic Impacts

Grant et al. ([26]) conducted a study of the impact on the Scottish economy of installing 3GW of Pelamis type devices within Scottish waters between 2006 and 2020. Their analysis considered how expenditures made across a number of industry sectors within Scotland would affect the Scottish economy. They show significant GDP and employment increase during and beyond the operating life of the marine devices. Several of the authors are presently pursuing a portfolio variance approach to evaluate future technology uptake.

6.3.3 Comparative Methods

For any marine energy scheme proposal, a wide range of economic indicators can be obtained and it is not straightforward to balance these to select appropriate designs. To facilitate technology selection (or site selection) whilst considering a wide range of variables (including economic, performance and environmental indicators), a comparative method may be employed. Stallard et al. ([27]) provide a brief background to such techniques and outline how they may be applied to the marine energy sector. A preliminary study was conducted for wave power devices but this type of approach can also be applied to tidal schemes.

6.4 REFERENCES

[1] Carbon Trust – *Future marine energy. Findings of the marine energy challenge: Cost competitiveness and growth of wave and tidal stream energy* – 2006, available at: http://www.thecarbontrust.co.uk

[2] Entec UK Ltd. commissioned by Carbon Trust – *Cost estimation methodology: the Marine Energy Challenge approach to estimating the cost of energy produced by marine energy systems* – 2006, available at: http://www.thecarbontrust.co.uk

[3] Previsic M., Siddiqui O., Bedard R. – *Economic Assessment Methodology for Wave Power Plants* – 2004, available at:
http://oceanenergy.epri.com/attachments/wave/reports/002_Rev_4_Econ_Methodology_RB_12-18-04.pdf

[4] Bedard R.., Siddiqui O., Previsic M. and Polagye B. – *Economic Assessment Methodology for Tidal In-Stream Power Plants* – 2006, available at:
http://oceanenergy.epri.com/attachments/streamenergy/reports/002_TP_Econ_Methodology_06-10-06.pdf

[5] Boehme, T., Taylor, J., Wallace, R. and Bialek, J. - *Matching renewable electricity generation with demand. Academic Study Summary* – 2006, Scottish Executive & University of Edinburgh, available at:
http://www.scotland.gov.uk/Publications/2006/04/24110728/0

[6] Boud, R. and Thorpe, T. - *WAVENET: Results from the work of the European Thematic Network on Wave Energy* - 2003.

[7] Black & Veatch - *The commercial prospects for tidal stream power* – 2001, ETSU T/06/00209/REP. DTI Sustainable Energy Programme DTI/Pub URN 01/1011.

[8] NORSOK - *Life cycle cost for systems and equipment* – 1996, Norsok Standard.

[9] Sinden, G. - *Variability of UK marine resources* - 2005, Environmental Change Institute (ECI) and The Carbon Trust.

[10] Awerbuch, S. - *Determining the real cost: Why renewable power is more cost-competitive than previously believed* – 2003, Renewable Energy World 6(2)52-61

[11] Cocodia , E.O. - *Creating better cost estimates for floating offshore structures by assessing cost correlation and understanding risk* – 2008, Proceedings of the 18th International Offshore and Polar Engineering Conference, July 2008, Vancouver, Canada.

[12] Atkins Oil & Gas - *A parametric costing model for wave energy technology* – 1992, ETSU-WV1685

[13] Thorpe, T. - *Economic analysis of wave power devices* – 1999, AEA Technology.

[14] Halcrow - *Wave Hub Technical Feasibility Study: Final Report* – 2005, South West of England Regional Development Agency

[15] Grainger and Jenkins - *Offshore Wind Farm Electrical Connection Options* – 1998, Proceedings of the 1998 Twentieth BWEA Wind Energy Conference.

[16] Garrad Hassan - *Offshore Wind: Economies of scale, engineering resource and load factors* - 2003, DTI and Carbon Trust Report 3914/BR/01.

[17] de Alegria, I. M., Martin, J.L., Kortabarria, I., Andreu, J. and Ibañez E., P. - *Transmission alternatives for offshore electrical power* – 2008, Renewable and sustainable energy reviews. (in press)

[18] DTI - *Economic Viability of a Simple Tidal Stream Energy Capture Device* – 2005, TP/3/ERG/6/1/15527/REP URN: 07/575.

[19] AMEC Wind - *Monitoring and Evaluation of Blyth Offshore Wind Farm. Projected Operation and Maintenance Costs of UK Offshore Wind Farms Based on the Experience at Blyth* – 2001, DTI Report W/35/00563/Rep/5 URN 04/881

[20] van Bussel, G.J.W. - *The Development of an Expert System for the determination of Availability and O&M costs for Offshore Wind Farms* – 1999, Proceedings of 1999 European Wind Energy COnference, Nice, France, 1999, pp402-405.

[21] Herman, S.A. - *Offshore Windfarms – Analysis of Transport and Installation Costs* – 2002, ECN-I-02-002, Energy Research Centre of the Netherlands, Petten, Feb 2002.

[22] IEA - *Offshore wind experiences* – 2006, International Energy Agency

[23] Junginger - *Learning in Renewable Energy Technology Development* – 2004, PhD Thesis, University of Utrecht.

[24] Chapman J and Gross R. - *Technical and economic potential of renewable energy generating technologies: potentials and cost reductions to 2020* - 2001, Performance and Innovation Unit report, The Strategy Office. Crown Copyright.

[25] Jeffrey, H. - *Learning rates in the marine energy sector* – 2008, 2nd International Conference on Ocean Energy, Brest, Brittany, October 2008.

[26] Grant, J.A., Bryden, I.G., McGregor, P.G., Stallard, T., Swales, J.K., Turner, K. and Wallace, R. - *Concurrent and legacy economic and environmental impacts from establishing a marine energy sector in Scotland* – 2008, Energy Policy 36(7) 2008, pp 2734-2753.

[27] Stallard T., Rothschild R. and Aggidis G.A. - *A comparative approach to the economic modelling of a large-scale wave power scheme* – 2008, European Journal of Operational Research 185, pp. 884-898

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

As it has been shown in the previous chapters, marine energy research has produced along the last decades a relevant amount of information that has favoured the birth and growth of a future industry. Many technical and non-technical challenges have been faced with a wide range of solutions and consistent theory, terminology and methodology has been defined for a large variety of technologies.

These conclusions, however, have been in many cases addressed considering specific objectives and purposes related to a particular type of device or deployment site and, even though many international networks have been established; a lot of research effort is still taking place at a local basis without the reference to standard procedures and to uniformly adopted parameters.

The increasing number of developers and stakeholders involved in marine energy determines therefore a need for a recognized set of approaches and guidelines that should ease the comparison between technologies and permit a common platform for communication and exchange of results between the researchers. The EquiMar project aims at defining some of these guidelines developing in some cases novel methods and results for subjects not extensively covered by the existing literature.

A primary objective of the project is therefore the identification of existing information that could constitute a basis for the protocols that will be defined during the execution of the project. The following sections give a global overview and preliminary evaluation of existing knowledge within the different areas outlined before. Some fundamental questions which arose from the analysis of the documents collected are briefly stated and intended to serve as a first indication and input to the other Work Packages.

7.2 MARINE ENERGY RESOURCE ASSESSMENT

Resource measurement and assessment has two fundamental objectives: providing an accurate measure of the available energy across a site and over the duration of a project and define the correct quantities to input for the performance assessment of the converters. This is why distinction is made between long-term and short-term assessment techniques.

Waves are usually described through the use of spectral analysis of time series of surface elevations and the resource is represented through power matrices that specify the occurrences of significant wave height and energy period. This seems to be nowadays almost a standard procedure among wave energy developers and researchers but perhaps not much effort has been devoted to actually verifying how efficiently this method describes wave resource.

The same choice of which parameters should be considered for a resource assessment is still questioned by some users and different selections can be found depending on the assessed site making wave resource assessment methods strongly site-specific. Debate has been growing also on which models to apply for correct description of a site resource: which spectrum is the “best one”? Which model is the most accurate in representing directional spreading? How and in which cases should spectral bandwidth and other parameters be taken into account? These are all questions for which no largely agreed answer has been found.

Also, the need for a uniform resource assessment procedure for site and technology comparison is coupled with the difficulty to define the degree of applicability to different sites as many of the recommended methodologies have been identified for specific places answering to particular needs and requirements. An extensive characterisation should address the uncertainties related to the assumed values and to this aim a probabilistic approach will be developed within the EquiMar project to check the accuracy of regional and global models.

Within the tidal assessment it has to be pointed out that most of the available tidal current data are only valid at the surface and assume that the velocity remains constant below the surface. Available energy is estimated broadly by applying fluids techniques more appropriate to wind but this does not take into account adequately the presence of the free surface and the bounding due to possible channel sides that might have an effect on the energy available at a site. The presence of the turbulence and its effect on the performance at a site is particularly complicated to be taken into account and no guidelines exist to deal with this factor that might determine differences in energy estimation from one site to another. Current tidal assessment procedures also lack of satisfactory characterisation of the interaction between surface waves and tidal currents, a point also to be analysed within EquiMar.

The differences between resource data representations make consultation of existing sources and databases on tidal and wave measurements difficult. There is also a divergence of availability of data between European countries.

Mathematical and numerical modelling techniques are improving all the time and are based on established theories and analytical models often developed for other marine applications. However, such techniques may not be comprehensive for end-users other than researchers and their direct applicability in the evaluation of sites and devices within the frame of large industrial projects may be questionable.

7.3 DEVICE MODELLING AND TESTING

Device modelling and general concept appraisal techniques have been a subject of research in various academic institutions and by developers. Verification and validation of a technology at a preliminary stage is usually carried out through the use of numerical and physical modelling techniques involving the definition of models that adequately describe the physical behaviour of the device.

Basic theory for marine energy devices has been developed by previous research works and contemporary application of well known formulations derived for the offshore structures and ships design. Some of these results represent also a benchmark for checking of the models.

Numerical modelling relies on mathematical approaches and computational tools. In many cases researchers and engineers working in the field develop their own code for assessment of marine energy devices and this makes the comparison between different technologies particularly complicated because of the different assumptions and level of detail of the models utilised. Commercial software is available for hydrodynamic modelling of the wave-body interactions and fluid flow description but such packages are generally designed for other applications and do not take into account specific needs of wave and tidal devices. Moreover there is no clarity among developers and researchers on which of these programs is more appropriate for a certain range of applications and what are the numerical uncertainties related to their use in the estimation of the performance.

Proof of concept is usually conducted through experimental testing in laboratories (wave and towing tanks and channels) where environmental conditions are simulated at appropriate scale. Guidelines and methodologies for testing have been indeed proposed by research teams working at lab facilities but these documents are often specifically applicable to particular types of facilities and/or devices and the choice of adequate parameters to describe the performance appears questioned by many. Agreement should be sought also on scaling operations and characterisation of representative environmental conditions.

Performance assessment of scaled devices is usually defined by power curves and power matrices but, as mentioned in the previous section, the choice and the measurement of the adequate parameters to be used as reference is still debated. In wave energy devices, spectral bandwidth, directionality and wave grouping might cause variation in the estimated output. For tidal devices wave-current interaction and turbulence and wake effects might be particularly crucial in performance estimation.

7.4 SEA TRIAL TESTING AND FULL-SCALE DESIGN AND DEPLOYMENT

Marine energy technologies need to be tested in real sea at a large scale to prove their effectiveness and feasibility for commercial exploitation. At the moment few devices have been tested in open sea conditions and even fewer have undergone sufficiently long testing periods to produce reliable data on their performance. Knowledge on methods and procedures for deployment coming from experience is therefore still limited and not exhaustive.

The recent development of purposely built open sea test sites has required the definition of appropriate procedures for performance measurement and representation. The usual indicators are based on power matrices for wave energy and power curves for tidal devices but, as mentioned before, a standard definition of these parameters has not yet been defined and is subject of ongoing international projects. The same selection of measurement instruments and sensors for monitoring operations appears still very device and site-specific and future protocols and guidelines should try to address this issue by considering different deployment locations and technology types.

Recommendations on design and manufacturing of marine energy devices have been defined by engineering companies and certification bodies, often basing many assumptions on previous experiences in the offshore oil & gas industry. However some of these conclusions are prone to be incorrect because of the difference in the risk factors in these sectors. Different operational conditions might also imply different survivability requirements for marine energy devices.

Reliability data and failure rates for many components might be available from other applications but should be critically assessed when applied to marine energy devices. For this purpose only future experience will allow the establishment of properly defined databases. Also, existing design criteria do not take into account site variability with sufficient detail. Work within EquiMar will address device classification and matching to the environment.

Another key issue is the design of moorings and foundations: although there is a good amount of guidance on mooring of one unit and even of several bodies interacting, the mooring for an array may be of a different challenge as cost of moorings for an array and the interaction between the units plus possible interference with single unit moorings may determine the moorings strategy for an array.

7.5 ENVIRONMENTAL IMPACT AND POLICIES

Marine Energies are lacking a common regulatory Framework in Europe. Some countries do not consider them yet in their Renewable Energy strategy plans and thus are not encouraging investment, while others are, but even these have different approaches regarding Environmental Impact Assessment requirements, consent procedures and tariffs.

How long does it take to obtain permits? Is it possible at all? How and where to plan a marine energy installation? What are the environmental implications and will they slow down the projects? An effort is needed to provide an overview about the situation of the policies nowadays and in the future.

Regarding Environmental Impact Assessments, the information on the impacts of marine energy converters is still too scarce and specific to particular projects and sites. Both administrations, as the bodies that grant permits, and developers need guidance to know:

- What environmental requirements ensure sustainability and which are negligible
- How to perform studies following best practices

What are the effects of marine energy farms on the long term? Do the impacts of different devices vary much? What is the most relevant factor; type of device, baseline state of the site, scale and number of deployments? Extensive research in the long term is needed to answer these questions, while the few experiences in marine energy and the ones that can be used from other industries such as offshore wind, point to the need for joining efforts and sharing information.

The aim of this project should be to produce practical guides to developers based on a four dimensional analysis of the projects: baseline environment, scale of device, type of device and activity phase of the project.

The uncertainties on the impacts on sensitive targets as marine mammals and other endangered species, call as well for research. As the marine environment is less known than the terrestrial one, best practices are needed to correctly assess the baseline environmental conditions of specific sites, taking into account that coastal areas have been under anthropic pressure for a long time and that degraded areas could even benefit from marine energy installations.

The same happens with monitoring of the effects once the projects are implemented; guidance on how to perform that environmental surveillance would be necessary to reach a better understanding of marine energies and the role they are going to play in the future, as well as of the marine environment itself.

Only a couple of life cycle analyses have been performed to date for marine energy devices. To carry out Life Cycle Analyses and couple them with Cost Benefit Analysis is an important tool to compare devices from an economic and environmental cost perspective.

7.6 ECONOMIC ASSESSMENT OF MARINE ENERGY TECHNOLOGIES

The limited experience of marine energy technologies generating electricity into the grid makes it particularly difficult to assess the economic feasibility of different device options for large-scale deployment.

Some previous studies have tried to estimate the cost of electricity by assuming relatively small deployments and partially neglecting implications of manufacturing, installation and operation. Other more advanced works have concentrated also on the development of different scenarios and application of learning curves to define a range of variability of the cost estimates.

Many cost models have been based on the Net Present Value approach but quite a lot of uncertainty can be found on how to take into account risk factors within the definition of proper discount rates. Other elements often neglected or poorly considered in the existing methodologies are the scalability of the costs with the deployment size and the device-specificity of some factors.

Determination of operational and maintenance costs is quite complicated because of the absence of reliable data on failures from real sea experience. Parametric models have been developed for this purpose but they do not seem to consider the problem of finding adequate site-access time windows because of environmental conditions.