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Published in the framework of the "Co-ordinated Action on Ocean Energy" (http://www.ca-oe.org)
EU project under FP6 *Priority*: 6.1.3.2.3; Renewable Energy Technologies

with the support of the **EUROPEAN COMMISSION**
Directorate-General for Research
under contract SES6-CT2004-502701

Produced by:
Centre for Renewable Energy Sources
Directorate for Renewable Energy Sources
Contact: Dr. Georgios Lemonis
19th km Marathon Ave.
GR-19009 Pikermi
Greece

e-mail: glemon@cres.gr
web: http://www.cres.gr

Ocean Energy Conversion in Europe

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Centre for Renewable Energy Sources
2006

A great deal of additional information on the European Union is available on the Internet.
It can be accessed through the Europa server (http://europa.eu).

Cataloguing data can be found at the end of this publication.

ISBN XX-XXX-XXXX-XX

Printed in Greece
PRINTED ON RECYCLED PAPER

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FOREWORD

"Climate change is not some vague future problem – it is already damaging the planet at an alarming pace" according to Time magazine April 2006 with a special report on global warming. Further it reads that "Chinas estimated rise in electricity demand by 2050 requires four 300 MW power stations build every week for 45 years".

Fortunately many countries in the world have understood the urgent need for pollution-free power generation, signed up to the Kyoto protocol and increased the amount of renewable energy production in their power production mix. Within this dynamic evolution of the renewable energy industry also an ocean energy industry is emerging. Ocean energy technologies are not yet economically competitive with more mature technologies, as e.g. wind energy and presently many different approaches to harvest Ocean Energy are being investigated.

The oceans cover 75% of the world surface and as such ocean energy is a global resource. There are different forms of renewable energy available in the oceans: waves, currents, thermal gradients, salinity gradients, the tides and others. Ways to exploit these high energy densities resources are being investigated worldwide.

With the financial support from the European Commission the *Coordinated Action on Ocean Energy* including 41 partners was launched in 2004. The partners share a common interest in the mutual benefit of cooperation, promotion and exchange of experience. Since the launch of the project there has been a steadily increasing interest in ocean energy conversion from governments and industry within EU and abroad.

The *Co-ordinated Action on Ocean Energy* has focused on Wave and Tidal Energy conversion. This publication is intended to give a snapshot of some of the ocean energy systems presently being tested at sea in Europe by the infant ocean energy industry.

On behalf of the Co-ordinated Action on Ocean Energy

Kim Nielsen, Co-ordinator

June 2006, Denmark

THE CO-ORDINATED ACTION ON OCEAN ENERGY

Scope and Objectives

In order to disseminate knowledge and promote sharing of information on Ocean Energy conversion, the *Co-ordinated Action on Ocean Energy* (http://www.ca-oe.org) was launched in October 2004 with scheduled duration of 3 years, in continuation to the *European Wave Energy Network* (http://www.wave-energy.net), which proved very successful in meeting these targets. The project is funded by the DG-Research of the European Commission within the 6th Framework Programme for Research and Technological Development.

The *Co-ordinated Action on Ocean Energy* involves the leading institutions in Europe in the field of Ocean Energy while the participating SME organizations are pioneers on the road to commercialisation of Ocean Energy systems. The partners cover a wide spectrum of disciplines, as basic and applied R&D, device development, industrial production or power supply.

The main objectives of the Co-ordinated Action on Ocean Energy are:

- To enable cooperation between all interested parties in this sector
- To promote and disseminate knowledge among stakeholders
- To develop a knowledge base for coherent development of R&D policies
- To bring a coordinated approach within key areas of ocean energy R&D
- To provide a forum for the longer term marketing of R&D deliverables

In the framework of its activities the *Co-ordinated Action on Ocean Energy* organizes dedicated interactive workshops every six month. The workshops will provide a forum to the different research organisations and the fledgling ocean energy industry to interact and co-ordinate ongoing R&D efforts on a European and international level. The project also provides grants for personnel mobility, conducts dissemination on various levels, stimulates international co-operation beyond the borders of the European Union and supports issues like implementation of guidelines and standards for Ocean Energy.

Project co-ordinator contact details:

Kim Nielsen
RAMBØLL Denmark A/S
Bredevej 2
2830 Virum
Denmark
http://www.ramboll-wave.com
e-mail: kin@ramboll.dk

Project participants

The project includes 41 partners from 12 countries within Europe and one partner from Canada. The contractors involved are divided in groups as follows:

Core-group

Co-ordinator	Rambøll	DK
Workshop organization	University of Strathclyde	UK
Dissemination	Centre For Renewable Energy Sources	GR
Website	University College Cork	IE
Training activities	Wave Energy Centre	PT

Ocean Energy Developers

Wave energy	Ocean Power Delivery Ltd	UK
	Teamwork technology BV	NL
	Queen's University Belfast	UK
	Instituto Superior Técnico	PT
	Aqua Energy UK, Ltd	UK
	Wave Dragon ApS	DK
	Ingenioerfirma Eric Rossen	DK
	Ocean Energy Limited	IE
	WavePlane Production A/S	DK
Tidal energy	IT Power	UK
	C J Day Associates	UK
	Ponte di Archimedes SpA	IT
	UNESCO-IHE Institute for water Education	NL
	Electricité de France	FR

R&D institutions

WP 1	Aalborg University (WP Leader)	DK
	The University of Edinburgh	UK
	Ecole Centrale de Nantes	FR
	Group ESIM	FR
	Bulgarian Ship Hydrodynamics Centre	BG
	University of Southampton	UK
	Ghent University	BE
	Universität Hannover	DE
WP 2	Uppsala University (WP Leader)	SE
	University of Patras	GR
	Swedish Seabased Energy AB	SE
	Chalmers tekniska högskola AB	SE
	Technische Universiteit Delft	NL
	Technische Universitaet Muenchen	DE
	National Technical University of Athens	GR
WP 3	Ecofys bv (WP Leader)	NL
WP 4	Instituto Nacional de Engenharia e Tecnologia Industrial	PT
	The Robert Gordon University	UK
	Powertech Labs Inc.	CA
	DHI Water & Environment	DK
	Lancaster University	UK
WP 5	SPOK Aps (WP Leader)	DK
	Institut Francais de Recherche pour lÉxploitation de la Mer	FR

Description of work

The *Co-ordination Action on Ocean Energy* will meet its objectives by organizing dedicated interactive workshops, as vehicles to enable cooperation between the interested European parties in the sector of Ocean Energy. This will strengthen any individual Ocean Energy program of generic or applied Research & Development. The proceedings from the Workshops will be made available on the project website www.ca-oe.org. The topics of the workshop (each from a work package) are:

- WP 1 Modelling of Ocean Energy Systems
  - 1.1 Numerical modelling
  - 1.2 Model test data

- WP 2 Component Technology and Power Take-off
  - 2.1 Mooring systems
  - 2.2 Installation methods
  - 2.3 Air turbines
  - 2.4 Water turbines
  - 2.5 Hydraulics
  - 2.6 Linear generators

- WP 3 System design, Construction, Reliability& Safety
  - 3.1 Verification of design codes & structural reliability
  - 3.2 Production & construction methods
  - 3.3 Deployment and maintenance procedures

- WP 4 Performance Monitoring of Ocean Energy Systems
  - 4.1 Monitoring and specifications of wave power converters
  - 4.2 Monitoring and specifications of tidal power converters
  - 4.3 Normalization and benchmarking of device performance

- WP 5 Environmental, Economics, Development Policy and Promotion
  - 5.1 Appraisal of environmental macro/micro economics
  - 5.2 Transportability of development policy between member states
  - 5.3 Tools for commercialisation of promising technologies
  - 5.4 Realizing wider socio-economic benefit
  - 5.5 Integration with other renewable and hydrogen

Another important aspect of the project is the component of personnel exchange which aims to strengthen the expertise by mobility and exchange of researchers. The *Co-ordinated Action on Ocean Energy* therefore includes funding to provide grants for short exchange visits, typically 2 weeks, to different institutions working in common areas.

Other activities include dissemination by various means to a wide range of stakeholders, organization of meetings and workshops above the project schedule, as well as stimulation of co-operation at international level beyond the borders of the European Union.

Results achieved so far

The main objective of bringing all the partners together has been a success. The project kick-off meeting was held one month after the project started in Copenhagen, Denmark. All partners attended and discussed the objectives and planning of the workshops. The partners were placed in groups as to their role in the project as a way to get to know each other. The day after the kick-off meeting a workshop on grid connection arranged by IEA-OES was made available for the partners followed by a technical tour to visit the Wave Dragon experiment in Nissum Bredning.

Workshop 1: Numerical and experimental modelling

The first workshop was held 4-5 April 2005 at Aalborg University, Denmark. The topic of the workshop was covered by a number of presentations on new modelling techniques and examples of testing ocean energy systems in various scales. The workshop provided the opportunity for Ocean Energy Developers to find additional expertise and help in device modelling and testing among the university partners of the project.

Pre-conference workshop to the 6th EWEC

The project partners decided to arrange a pre-conference workshop before the 6th European Wave Energy Conference (30 Aug. – 4 Sept. 2005, Glasgow) in order this co-ordinated action to be promoted to a wider audience.

Following this pre-conference workshop, the initiative to form a **European Ocean Energy Association** (http://www.eu-oea.com) was taken, to promote development toward implementation and commercial exploitation. The five corporate founders and first directors of the association are:

- Mrs. Alla Weinstein (first chairman) of AquaEnergy Development Ltd, UK
- Mr. Kim Nielsen of Rambøll, DK
- Mr. Tom Thorpe of Oxford Oceanics, UK
- Mr. Hans Christian Sørensen of Wave Dragon Asp, DK
- Mr. Antonio Sarmento of the Wave Energy Centre, PT

Workshop 2: Component Technologies and Power Take-off

The second workshop was held 1-2 November 2005 in Uppsala University, Sweden. The topic of this workshop was covered by a number of presentations on different power take–off systems such as linear generators transforming the oscillating forces and movements directly into electricity, oil hydraulic systems as used in the Pelamis project, water turbines as used in the Wave Dragon device and air turbines as used in oscillating water columns, e.g. the Pico plant and the Limpet system. Presentations on other components such as moorings were also made and discussed.

Workshop 3: System design, Construction, Reliability& Safety

The third workshop was arranged 29-30 March 2006 by Ecofys, NL, in Amsterdam. The topic of this workshop was in contrast to the proceeding workshops covered in a more interactive way. Key speakers from DNV and Germanisher Loyd were invited to the workshop to give presentations on the new standards drafted for ocean energy, followed by various presentations illustrating the issues. In the subsequent group work the partners exchanged their experiences in relation to the topics and provided focused input on priorities for further R&D.

Expected Results

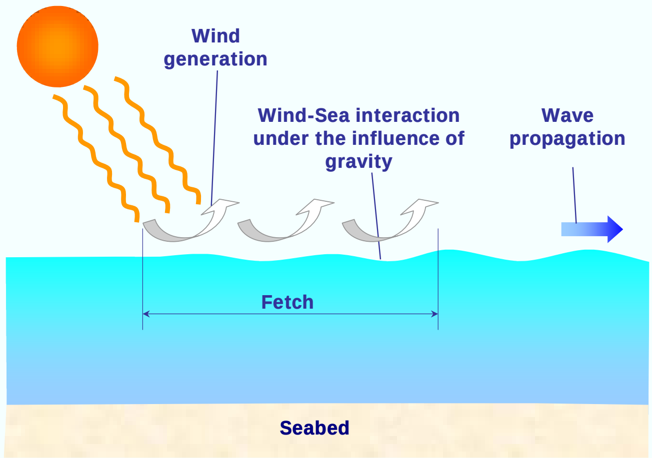
The *Co-ordinated Action on Ocean Energy* is expected to promote and disseminate promising methodologies and technologies in the field of Ocean Energy systems and generate awareness to a wider public worldwide.

The frequent workshops between the partners and the possibility to arrange exchange visits also are expected to generate clusters of research groups that will focus on research activities of common interest. In addition, activities outside the workshops have been initiated, as provision of exposition material, setup of a roadmap for development of Ocean Energy, planning the 7th European Wave Energy Conference, as well as inclusion of partners from various countries from the Americas, Asia and Australia.

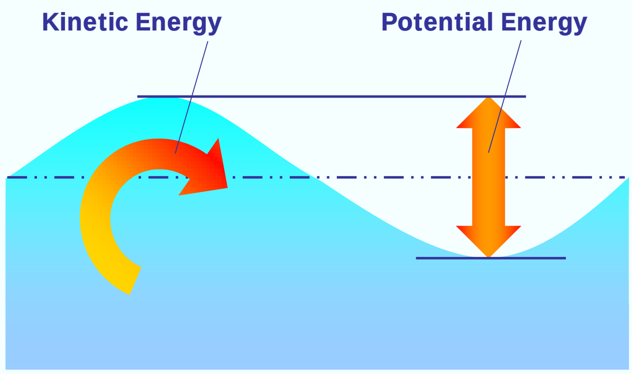
WAVE ENERGY

Wave Energy Physics and Resource

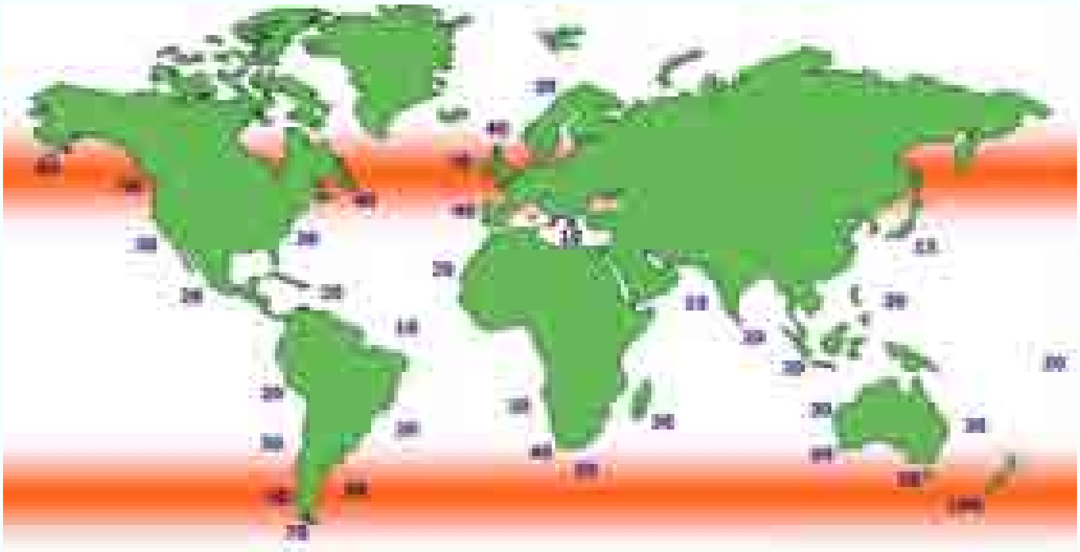
Among different types of ocean waves, wind generated waves have the highest energy concentration. Wind waves are derived from the winds as they blow across the oceans. This energy transfer provides a natural storage of wind energy in the water near the free surface. Once created, wind waves can travel thousands of kilometres with little energy losses, unless they encounter head winds. Nearer the coastline the wave energy intensity decreases due to interaction with the seabed. Energy dissipation near shore can be compensated by natural phenomena as refraction or reflection, leading to energy concentration ("hot spots").



Ocean waves encompass two forms of energy: the kinetic energy of the water particles, that in general follow circular paths; and the potential energy of elevated water particles. On the average, the kinetic energy in a linear wave equals its potential energy. The energy flux in a wave is proportional to the square of the amplitude and to the period of the motion. The average power in long period, large amplitude waves commonly exceeds 40-50 kW per meter width of oncoming wave.



As most forms of renewables, wave energy is unevenly distributed over the globe. Increased wave activity is found between the latitudes of ~30° and ~60° on both hemispheres, induced by the prevailing western winds (Westerlies) blowing in these regions. Particularly high resources are located along the Western European coast, off the coasts of Canada and the USA and the southern coasts of Australia and South America.



Situated at the end of the long fetch of the Atlantic, the wave climate along the western coast of Europe is highly energetic. Higher wave power levels are found only in the southern parts of South America and in the Antipodes. Resource studies assign for the area of the north-eastern Atlantic (including the North Sea) available wave power resource of about 290 GW and for the Mediterranean 30 GW.

Principles and Aspects of Wave Energy Conversion

In contrast to other renewable energy sources the number of concepts for wave energy conversion is very large. Although over 1000 wave energy conversion techniques are patented worldwide, the apparent large number of concepts for wave energy converters can be classified within a few basic types:

- **Oscillating Water Columns** are partially submerged, hollow structures open to the seabed below the water line. The heave motion of the sea surface alternatively pressurizes and depressurizes the air inside the structure generating a reciprocating flow through a turbine installed beneath the roof of the device.

- **Overtopping devices**, floating or fixed to the shore, that collect the water of incident waves in an elevated reservoir to drive one or more low head turbines.

- **Heaving devices** (floating or submerged), which provide a heave motion that is converted by mechanical and/or hydraulic systems in linear or rotational motion for driving electrical generators.

- **Pitching devices** that consist of a number of floating bodies, hinged together across their beams. The relative motions between the floating bodies are used to pump high-pressure oil through hydraulic motors, which drive electrical generators.

- **Surging devices** that exploit the horizontal particle velocity in a wave to drive a deflector or to generate pumping effect of a flexible bag facing the wave front.

It is important to appreciate the difficulties facing wave power developments, the most important of which are:

- Irregularity in wave amplitude, phase and direction; it is difficult to obtain maximum efficiency over the entire range of excitation frequencies.

- The structural loading in the event of extreme weather conditions, such as hurricanes, may be as high as 100 times the average loading.
- The coupling of the irregular, slow motion (~0.1 Hz) of a wave to electrical generators requires typically ~500 times greater frequency.

Obviously the design of a wave power converter has to be highly sophisticated to be reliable and safe on the one hand, and economically feasible on the other. The abundant resource and the high-energy fluxes in the waves prescribe economically viable energy production. One of the important advantages of wave energy technologies is their environmental compatibility, as wave energy conversion is generally free of polluting emissions. Also, the low visual and acoustic impact, particular of offshore or submerged devices, is a major advantage over e.g. wind energy or photovoltaics. The negligible demand of land use is an important aspect, followed by the current trends of offshore wind energy exploitation. As for most renewables, the in-situ exploitation of wave energy implies diversification of employment and security of energy supply in remote regions. Furthermore, the large-scale implementation of wave power technologies will stimulate declining industries, e.g. shipyards, and promote job creation in small and medium-sized enterprises.

Wave Energy Development Status

Wave energy conversion is being investigated in a number of countries, particularly in the member States of the European Union, Canada, China, India, Japan, Russia, the USA and others. Although the first patent certificate on wave energy conversion was issued as early as 1799, the intensive research and development study of wave energy conversion began after the dramatic increase in oil prices in 1973.

In the last five years there has been a resurgent interest in wave energy, especially in Europe. Nascent wave energy companies have been highly involved in the development of new wave energy schemes such as the Pelamis, the Archimedes Wave Swing or the Wave Dragon. The potential worldwide wave energy contribution to the electricity market is estimated to be of the order of 2,000 TWh/year, about 10% of the world electricity consumption.

The predicted electricity generating costs from wave energy converters have shown a significant improvement in the last twenty years, which has reached an average price below 10 c€/kWh. Compared, e.g., to the average electricity price in the European Union, which is approx. 4 c€/kWh, the electricity price produced from wave energy is still high, but it is forecasted to decrease further with the development of the technologies.

Although early programmes for research and development on wave energy considered designs of several MW output power, recent designs are rated at power levels ranging from a few kWs up to some MWs. Massive power production can be achieved by interconnection of large numbers of devices.

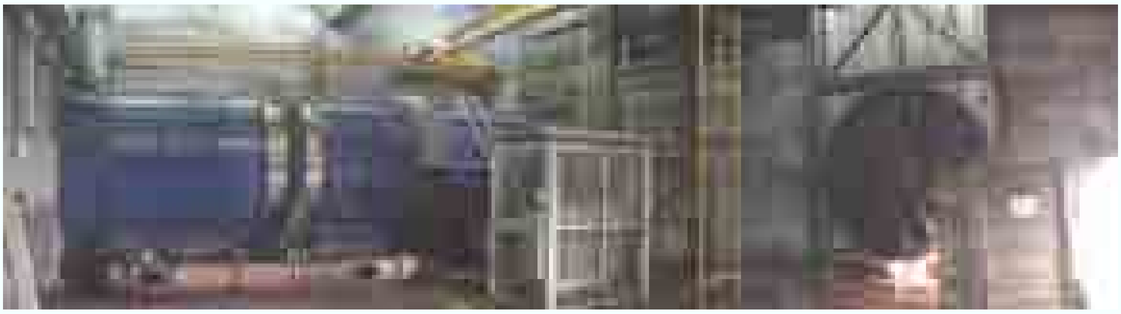
The amount of ongoing development work on wave energy technologies is very large, and cannot be done justice in a single presentation. Here, some of the promising technologies will be presented that have progressed to open sea testing. For ease of presentation the devices are categorised according to the distance of the location of installation from the shore.

Shoreline Devices

Shoreline devices are fixed to or embedded in the shoreline, having the advantage of easier installation and maintenance. In addition shoreline devices do not require deep-water moorings or long lengths of underwater electrical cable. However, they would experience a much less powerful wave regime. This could be partially compensated by natural energy concentration ("hot spots"). Furthermore, the deployment of such schemes could be limited by requirements for shoreline geology, tidal range, preservation of coastal scenery etc. The most advanced class of shoreline devices is the oscillating water column. Two of the OWC wave power plants developed in Europe are the following:

European Pilot OWC Plant

The wave power plant at the island of Pico, on the Azores (PT), is a 400 kW rated shoreline Oscillating Water Column equipped with a Wells turbine. The Pico plant was built between 1995 and 1999, under the co-ordination of Instituto Superior Técnico (PT), http://www.ist.utl.pt, co-funded by the European Commission. Flooding and malfunction problems affected the commissioning of the plant and delayed the testing programme.



In 2003, the Wave Energy Centre, a recently founded Portuguese Association dedicated to the development and promotion of wave energy, received a grant to refurbish the plant and recommence testing. The works started in 2004 and real sea testing was initiated in September 2005. The plant is presently undergoing inspection and maintenance, the testing programme being expected to continue in spring 2006.

Based on the experience of the Pico OWC a “wave energy breakwater” project is currently being developed as a commercial approach. The device will be integrated in a caisson breakwater head under construction at the Douro estuary in Oporto/Northern Portugal. The project is supported by national funds, essentially financed by the EDP-group (Electricity of Portugal).

After the concession of the breakwater construction in 2004, a Consortium has proceeded with the overall design concerning the integration of an OWC into the breakwater. The possibility of using two chambers with independent turbo-generator groups is presently being discussed among the involved institutions.

Limpet OWC

The Limpet OWC, developed by WaveGen Ltd. (UK), http://www.wavegen.com, has been commissioned in December 2000 on the Island of Islay, off the west coast of Scotland. The OWC feeds a pair of counter-rotating Wells turbines each of which drives a 250kW generator, giving a nameplate rating of 500kW.

After being in grid connected operation for nearly 2 years the Limpet OWC has demonstrated the capacity of wave generated electricity to contribute to a national grid supply. Both the collector and the turbo-generation equipment have proved robust and have survived extremes of weather with minimum maintenance. This demonstrates that wave energy can be extracted in a low maintenance environment.

Overall the project has been a success as a technology demonstrator, as a platform for testing equipment and as a vehicle for gaining operational experience relevant to both shoreline and offshore generators. The plant will continue to operate supplying the national grid and will serve as a test bed for future power take off systems.

Wavegen and SEV, the Faroese electricity company, are currently jointly developing a wave power station based on a series of OWC-turbine power generation modules. The key innovative feature is the use of tunnels cut into the cliffs on the shoreline to form the chamber which captures the energy. The new design offers a novel and complementary approach to shoreline devices that is well-protected and unobtrusive.

Near shore Devices

Near shore devices are deployed at moderate water depths (~20-30 m), at distances up to ~500 m from the shore. They have nearly the same advantages as shoreline devices, being at the same time exposed to higher wave power levels.

Wave Energy Point Absorber

This point absorber system is developed by Wave Energy S.A. (GR), http://www.wave-energy.gr. The wave motion is converted to high pressure hydraulic energy by a floater driving a piston system anchored to the seabed. The piston system pressurizes seawater to ~200 bar, which is transferred to the shore to drive a hydraulic motor and produce electricity, or used for desalination by inversed osmosis.

The development of the device started in 2002. Today there have been successfully completed various full scale tests in depths of approx. 10-20 m. However, the device can be installed in greater depths with little head losses. The piston system is common for both operating modes (power production or desalination).

For power production, the pressurized water is supplied to a power take off system onshore, which comprises a patented smoothing accumulator and a hydraulic motor. The motor drives a synchronous generator at ~3000 rpm. In the case of a floater array, several floaters are connected to a common PTO. The electrical power output is estimated to ~2-3 kW per floater at moderate wave power levels (~10 kW/m).

For desalination, the pressurized water is supplied to an inverse osmosis device. Hourly production of potable water is being estimated at ~2000 lt per floater.

WaveRoller

The WaveRoller device, developed by AW Energy Oy (FI), http://www.aw-energy.com, is a submerged plate anchored in vertical position on the sea bed at moderate water depths (i.e up to ~20 m). The back and forth movement of bottom waves moves the plate, and the kinetic energy produced is collected by a piston pump. This energy can be converted to electricity either by a generator linked to the WaveRoller plate, or by a closed hydraulic system in combination with a generator/turbine system.

The nominal power output of one single plate is of the order of 13kW. WaveRoller uses a modular concept combining 3-5 plates installed into a common framework. The system is scalable and there is no technological upper limit for the plant capacity. Typical depth for installation is about 7-15 meters. As with all submerged wave energy conversion devices the device is characterized by low visual and acoustic impact.

During 1999 and 2004 the WaveRoller device has undergone numerical modelling and laboratory testing at small scales in Finland. In 2005 open sea tests with semi-scale (1:3) prototypes were conducted at the European Marine Energy Center in Orkney (UK) and in Equador. The tests aimed to prove the strength of bottom waves and the technical viability of the technology. The short term plans of the company include realization of a pilot plant of 1 MW capacity in 2007 to demonstrate the full size system performance.

Offshore Devices

This class of device exploits the more powerful wave regimes available in deep water (>40m depth). More recent designs for offshore devices concentrate on small, modular devices, yielding high power output when deployed in arrays. Some of the promising offshore wave energy converters developed are the following:

Archimedes Wave Swing

The Archimedes Wave Swing (AWS), originally developed by Teamwork Technology BV (NL), http://www.waveswing.com, the rights now owned by AWS Ocean Energy LTD (UK), http://www.awsocean.com, consists of a hollow, pressurized steel structure, the upper part of which is initiated to heave motions by the periodic changing of hydrostatic pressure beneath a wave. Being submerged, the device is characterized by low visual and acoustic impact.

Following to numerical and laboratory testing from 1995 to 2003, a 2 MW prototype was installed in 2005 offshore Portugal, which was tested for seven months. During this period the system supplied into the 15kV local grid and demonstrated its controls and reliability. The results gave confidence in the direct drive-permanent magnet-linear generator technology employed in the AWS.

The company now focuses on the development of a new model (AWS II), the design of which is based on the experiences with the original AWS. AWS II is a tension leg submerged platform which will not use the fixed pontoon system of the original design. At present the device design is finished and the preparation is started to manufacture and install a pre-commercial demonstrator. The rated power will be 1

MW and it will be the first device of a wave energy farm. The AWS II is designed to be maintenance friendly needing visual inspection and minor maintenance once in three years, and general maintenance once in ten years.

Pelamis

The Pelamis, developed by Ocean Power Delivery Ltd (OPD, UK), http://www.oceanpd.com, is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. Several devices can be connected together and linked to shore through a single seabed cable. The machine is held in position by a patented mooring system.

In the period 1998 – 2004 Pelamis has been undergone wave tank and open sea testing at scales ranging from 1/80 to 1/7. In 2004 a 750 kW commercial-scale prototype was installed at the European Marine Energy Centre in Orkney. The prototype is 120m long, 3.5 m in diameter and contains three 250 kW power modules.

Following to the successful prototype tests, OPD signed in 2005 an order with a Portuguese consortium to deliver early 2006 three 750kW Pelamis machines with a combined rating of 2.25MW. The machines will undergo final assembly at Port of Peniche prior to installation 5km off northern Portugal. A letter of intent has also been signed to order a further 28 Pelamis machines subject to satisfactory performance of the initial phase. The eventual 22.5MW project will meet the electricity demand of 15,000 households whilst displacing annually more than 60,000 tonnes of carbon-dioxide emissions.

PowerBuoy

The PowerBuoy is a point absorber developed by Ocean Power Technologies (USA), http://www.oceanpowertechnologies.com. The system uses an ocean-going buoy to capture and convert wave energy into electricity via a patented power take-off. The generated power is transmitted ashore via an underwater power cable. In the event of extreme waves, the system automatically locks-up and ceases power production. When the wave heights return to normal, the system unlocks and recommences energy conversion and power transmission. The PowerBuoy, which utilizes conventional mooring systems, can be deployed in arrays scalable to 100's of megawatts.

Commencing in 1997, the PowerBuoy has undergone ocean testing in the Atlantic and Pacific Oceans. In June 2004 and October 2005 40 kW units have been deployed off the coast of Oahu, Hawaii, to demonstrate wave power for use at US Navy bases. Another 40 kW demonstration unit was put in operation in October 2005 at Atlantic City, New Jersey.

Early 2006 the company will begin the first phase of installation of a 1.25 MW wave farm off the northern coast of Spain. The project is a joint venture with the Spanish utility Iberdrola and it is expected to be operational in 2007. In addition, a full size demonstration plant of up to 10MW capacity is planned for installation in the UK.

Wavebob

The Wavebob, developed by Wavebob Ltd (UK), http://www.clearpower.ie, comprises a wave energy absorber and a hydraulic power take-off system driving synchronous alternators. The absorber is an axi-symmetric, compound, and self-reacting oscillator operating primarily in the heave mode. The Wavebob is being designed for offshore deployment in large arrays. Commercial units will have a concrete structure floating on compliant moorings with an expected lifetime of 20 years.

The power take-off system of the WaveBob device is modular, safely accessible, and it is designed to have low operating and maintenance costs. Fully autonomous on-board control will facilitate good prediction of power output to the grid. Each Wavebob unit will carry three 0.5MW alternators (giving in total a rated output of 1.5MW) driven at constant speed by hydraulic motors operating off oil pressure accumulators. The preferable depths of deployment are greater than 70m, readily available in the energetic waters of the North Atlantic off Western Europe.

In the past years the concept has been analysed, and the theoretical basis, which comprises frequency and time-domain simulation models, has been verified by independently run tank tests at various scales. A semi-scale (1:4) prototype is currently being tested in Galway Bay in Northern Ireland. One of the aims of these tests is the verification of the time domain modelling approach to explore alternatives, and to test for an optimum device performance.

Wave Dragon

The Wave Dragon is an offshore overtopping device developed by a group of companies led by Wave Dragon ApS (DK), http://www.wavedragon.net. It utilizes a patented wave reflector design to focus the wave towards a ramp and fill a higher-level reservoir. Electricity is produced by a set of low-head Kaplan turbines.

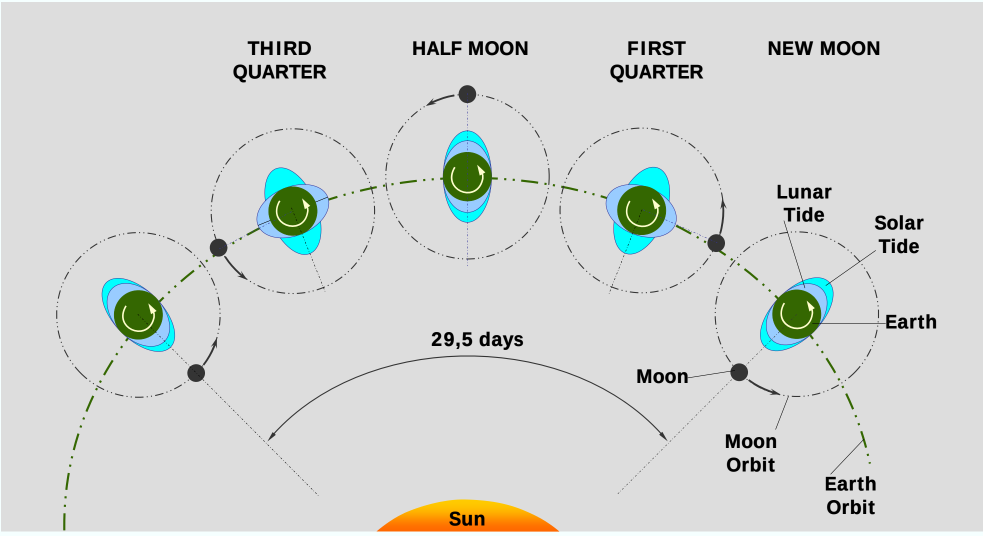
From 1998 onwards the performance of Wave Dragon has been optimised through numerical modelling and wave tank testing. The optimisations focused especially on the reflector design and the cross section of the ramp, and have almost doubled the energy capture compared to the 1st generation design. In May 2003, a 57 x 27 m wide and 237 tonnes heavy 1:4,5 scaled prototype was installed and grid connected in Nissum Bredning. The prototype is fully equipped with hydro turbines and automatic control systems, and is instrumented in order to monitor power production, wave climate, mooring forces, stresses and device motion.

Recently, Wave Dragon ApS received from the Welsh Assembly Government confirmation for a multi-MW demonstration project. It involves the two stage development, financing, construction and operation of up to 77MW of wave generated electricity in Wales. The first stage of project development comprises the deployment of a 7MW Wave Dragon unit off the coast of West Wales, near Milford Haven. The unit is projected to provide sufficient electricity to power up to 6,000 homes.

TIDAL ENERGY

Tidal Energy Physics and Resource

Tidal energy conversion techniques exploit the natural rise and fall of the level of the oceans caused principally by the interaction of the gravitational fields in the planetary system of the Earth, the Sun and the Moon. The main periods of these tides are diurnal at about 24 h and semidiurnal at about 12 h 25 min. During the year, this motion is being influenced by the positions of the three planets with respect to each other. Spring tides occur when the tide-generating forces of the Sun and the Moon are acting in the same directions. In this situation, the lunar tide is superimposed to the solar tide. Some coastlines, particularly estuaries, accentuate this effect creating tidal ranges of up to ~17 m. Neap tides occur when the tide-generating forces of the sun and the moon are acting at right angles to each other.



The vertical water movements associated with the rise and fall of the tides are accompanied by roughly horizontal water motions termed *tidal currents*. It has therefore to be distinguished between *tidal range energy*, the potential energy of a tide, and *tidal current energy*, the kinetic energy of the water particles in a tide.

Tidal currents have the same periodicities as the vertical oscillations, being thus predictable, but tend to follow an elliptical path and do not normally involve a simple to-and-fro-motion. Where tidal currents are channelled through constraining topography, such as straits between islands, very high water particle velocities can occur. These relatively rapid tidal currents typically have peak velocities during spring tides in the region of 2 to 3 ms^{-1} or more.

Currents are also generated by the winds, and temperature and salinity differences. The term “marine currents”, often met in literature, encompasses several types of ocean currents. Wind driven currents affect the water at the top of the oceans, down to about 600-800 m. Currents caused by thermal and salinity gradients are normally slow, deep water currents, that begin in the icy waters around the north polar ice. Wind driven currents appear to be less suitable for power generation than tidal currents, as they are in general slower. Moreover, tidal currents exhibit usually their maximum speed at comparably shallow waters accessible for large engineering works.

The global tidal range energy potential is estimated to be about 3 TW, about 1 TW being available at comparably shallow waters. Within the European Union, France and the United Kingdom have sufficiently high tidal ranges of over 10 metres. Beyond the European Union, Canada, the CIS, Argentina, Western Australia and Korea have potentially interesting sites, which have been periodically investigated. Some regions with exceptional tidal range are shown on the next figure (annual average tidal range in meters).

Recent studies indicate that marine currents have the potential to supply a significant fraction of future electricity needs. The potential for marine current turbines in Europe is estimated to exceed 12,000 MW of installed capacity. Locations with especially intense currents are found around the British Islands and Ireland, between the Channel Islands and France, in the Straits of Messina between Italy and Sicily, and in various channels between the Greek islands in the Aegean. Other large marine current resources can be found in regions such as South East Asia, both the east and west coasts of Canada and certainly in many other places around the Globe that require further investigation.

Principles and Aspects of Tidal Energy conversion

Tidal Range Energy

The technology required to convert tidal range energy into electricity is very similar to the technology used in traditional hydroelectric power plants. The first requirement is a dam or "barrage" across a tidal bay or estuary. At certain points along the dam, gates and turbines are installed. When there is an adequate difference in the elevation of the water on the different sides of the barrage, the gates are opened. The "hydrostatic head" that is created, causes water to flow through the turbines, turning an electric generator to produce electricity.

Tidal range energy conversion technology is considered mature, but, as with all large civil engineering projects, there would be a series of technical and environmental risks to address. One major environmental risk is associated with the changes of water levels which would modify currents, and sediment transport and deposit. However, there are regional development benefits as well, for example the La Rance plant in France, the only commercial sized tidal range conversion scheme so far, includes a road crossing linking two previously isolated communities and has allowed further development of the distribution network for raw materials and developed products.

Tidal Current Energy

Tidal currents can be harnessed using technologies similar to those used for wind energy conversion, i.e. turbines of horizontal or vertical axis (“cross flow” turbine). Some other techniques have either been abandoned or are at an early stage of development.

Several types of tidal current conversion devices, particularly fully submerged devices, are subject to the corrosive effects of seawater. This leads to high material and construction costs. In addition, maintenance is difficult because divers are needed to access submerged machinery. While placing the drive train above water can minimize the need for divers, maintenance costs would remain higher than e.g. in wind turbines.

In contrast to atmospheric airflows the availability of tidal currents can be predicted very accurately, as their motion will be tuned with the local tidal conditions. Because the density of water is some 850 times higher than that of air, the power intensity in water currents is significantly higher than in airflows. Consequently, a water current turbine can be built considerably smaller than an equivalent powered wind turbine.

Another specific advantage of tidal current devices is the limited environmental impact. Their installation requires minimal land use, and fully submerged devices will not affect optically or acoustically their surroundings. Their effects on flora or fauna have not been studied extensively yet, but it is unlikely that they will be of significance. Finally, submerged marine current converters are considered to operate in safe environment: disturbances caused by extreme weather conditions are significantly attenuated to the depths of about 20-30 metres where the devices will normally operate.

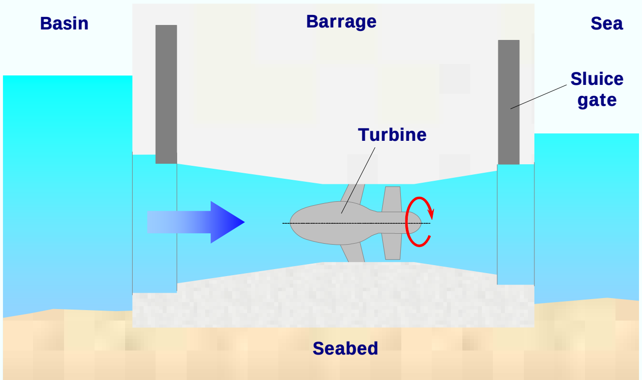
Tidal Energy Development Status

Tidal Range Energy

Tidal range energy projects require normally high capital investment at the outset, having relatively long construction periods and long payback periods. Consequently, the electricity cost is highly sensitive to the discount rate used. Access to suitable funding is thus a serious problem, and is unlikely without public intervention.

The first large scale, commercial plant was built on the Rance estuary in France during the 1960's and has now completed over 40 years of successful operation. The La Rance station is still the only industrial-sized tidal power station worldwide. Its 240

MW power is about 1/5th of an EDF (Electricité de France) nuclear reactor and is more than 10 times the power of the biggest among the other tidal stations in the world.



The good performance of La Rance has resulted in examination of additional projects in France, which were finally abandoned because of their high investment costs and environmental concerns. Various other smaller plants have been built in Russia, Canada and China. In the UK a series of industrial consortia have investigated the prospects for tidal energy on the Severn, Mersey and a number of smaller estuaries.

The comparably high generation costs and long payback periods of shoreline tidal range schemes imply that within deregulated electricity markets, which are based on private investment, tidal energy is unlikely to be commercially developed, if the kWh price does not become competitive to cost-effective renewable energies. The development of *offshore* tidal range energy could resolve many of the financial and environmental constraints of shoreline tidal range energy.

Tidal Current Energy

Tidal current technology is in its infancy. Recent developments open up prospects for commercial deployment of some schemes in the near future. The economical viability of these schemes is proven yet, but it is anticipated that the production costs will decrease as the technologies advance. At present, different pilot plants are in operation or about to be installed, mainly in Europe. Most devices rely on the horizontal or vertical axis turbine concepts.

Kobold

The Kobold device, developed by Ponte di Archimede SpA (IT), http://pontediarchimede.com, is a vertical axis tidal current turbine. Its development started in 1995 based on the concept for a simple and reliable current converter.

The device employs a patented, vertical axis rotor driving a synchronous generator. An important feature of the Kobold is that the direction of rotation of the rotor is independent of the current direction.

The Kobold device was optimized by numerical modelling and towing tank testing with a 1:4.5 scale model. In 2002 a prototype was deployed in the Strait of Messina and it continues since then grid connected operation. The plant is positioned about 150 – 200 m from the shore. The depth ranges from 15 to 35 m and the maximum current speed is around 2.0 m/s although there are places in the Strait of Messina where the current speed can be more than 3.0 m/s.

The rotor has a diameter of 6 m and consists of three blades with a span of 5 m each. It drives an alternator through an epicycloidal overgear. The system is mounted on a floating steel platform of 10 m diameter. The platform is moored to the seabed by means of four mooring lines.

The tests indicate that the turbine produces 25 kW of power in a current speed of 1.8 m/s. In a current of 3.0 m/sec 80 kW are expected. The device is equipped with a photovoltaic roof which is parallel connected to the local grid.

SeaFlow

The SeaFlow device is developed by Marine Current Turbines Ltd. (UK), http://www.marineturbines.com. The device consists of a horizontal axis rotor mounted on a steel mono-pile set into a socket drilled in the seabed.

Preliminary development work was carried out in the period 1999 – 2002 and included open sea tests with a 15 kW unit with a 3.5 m diameter rotor. In 2003 a prototype was successfully installed and commissioned 1km off Foreland Point, near Devon, UK, at a depth of 30 m. The device has a rotor of 15 m of diameter and it can generate a maximum of 300kW in a 2.7m/s current. A key patented feature of the technology is that the rotor and drive train can be raised completely above the surface for maintenance.

The SeaFlow device has meanwhile passed a period of 3 years of operation confirming the technical viability of the concept for mono-pile mounted tidal turbines. Recent work has involved automation of operation and measurements relating to environmental impact, including underwater noise measurements and wake measurements to determine the turbine's "footprint" in the tidal flow.

In 2006 the company received permission to install at Strangford Lough, Northern Ireland, SeaGen, a 1 MW “twin-rotor” tidal current device, which will confirm the potential for commercial success of the technology. The device will be grid-connected and will function with the flow in both directions. The company also explores the feasibility of building a 10 MW tidal farm with 12 units off Foreland Point on the north Devon coast.

Tocardo

The Tocardo device, which is developed by Teamwork Technology BV (NL), http://www.teamwork.nl, is a horizontal axis marine current turbine. It is designed for installation in the exhaust flumes of the various storm barrages in Holland.

The present design, which evolved from comparison of different methodologies, is conventional, using a two bladed, fixed pitch, variable speed rotor of 2.8 m diameter and a gearbox. A first unit was tested in Holland in an exhaust flume in 2006 where during low tide the water from the IJselmeer in the Netherlands flows into the North see with max. water velocity of 4.5 m/s. The device is rated with 35 kWe at current speed of 3.2 m/s. During the demonstration period electricity was supplied to the grid.

The device control is adaptive, in which the system finds its optimal flow/ rotation speed ratio automatically. In the commercial series the gearbox will be replaced by a direct drive permanent magnet generator. The lifetime of the device is estimated at 25 years, with a need of overall maintenance only every ten years.

The first commercial applications of the turbines will be in existing storm barrages that are in the Netherlands at several places. Together with the ongoing project for the installation of three systems in the Afsluitdijk by November 2006, a study to install ten systems in the Oosterschelde dam is performed, the capacity of which is estimated to at least 100 – 200 MW. The installation in the Oosterschelde dam is expected for 2007- 2008.

Centre for Renewable Energy Sources

Ocean Energy Conversion in Europe - Recent Advancements and Prospects

2006 –36 pp. – 21.0 x 29.7 cm

ISBN XX-XXX-XXXX-X

Ocean energy is an abundant renewable resource, which is starting to be exploited by several European countries. Considerable progress has been made over the past decade in this sector in Europe, resulting in some technologies being at, or near, commercialization; others still require further research. This huge work is being supported by national Programmes and the Programmes for research, technological development and demonstration of the European Commission, which have stimulated coordinated working in this field among the European countries and have significantly contributed to the progress in wave energy utilization in Europe.

Following the success of the *European Thematic Network on Wave Energy* (2000-2003), a further step to facilitate collaboration between European countries in the Ocean Energy sector has been taken through the formation of the **Co-ordinated Action on Ocean Energy**. This project was launched in 2004 with participation of over 40 ocean energy representatives from various European countries in the frame of the *Sixth Framework Programme for Research, Technological Development and Demonstration* of the European Commission. Its main targets are the co-ordination and the improvement of the interactions between major players in Ocean Energy and the establishment of synergies in Ocean Energy utilization.

This publication, produced in the framework of the promotional activities of the **Co-ordinated Action on Ocean Energy**, renders the current status of Ocean Energy utilization in Europe and highlights the potential for innovative Ocean Energy technologies to become widely applied and contribute superior services to the citizen.

Along with the other promotional activities of the project, which include publications in international journals, the establishment of an internet website and the support of workshops and conferences, this brochure intends to raise the profile and general understanding of Ocean Energy by a range of target groups in Europe, like the general public, policy makers, potential investors, planners and electricity utilities.

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